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Perception of the direction of articulatory motion of point-light figures

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Supervisor: Prof. Dr. Karl Verfaillie
Co-supervisor: Dr. Ben Schouten

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Observing and interpreting the direction of human movements and actions are necessary to interact effectively and efficiently with other human beings. For instance, predicting the speed with which an elder steps back from an angry dog may increase her/his safety because we would be able to intervene and prevent an attack. From an experimental perspective, the study of the perception of the direction of articulatory human motion may be traced back to the original theoretical perspective and procedures introduced by Johansson (1973) to study perceptual organization. Remarkably, the author was able to create a stimulus consisting of a number of point-lights that represent some of the joints of a person to elicit perception of human motion in laboratory contexts very similar to our perception in daily life: the biological motion stimulus.

As the present dissertation deals with a study of the perception of the direction of articulatory motion of human actions depicted as point-light displays, it seems reasonable to follow Johansson's ideas about the way to analyze the stimulus –using physical concepts- and the kind of research he expected to have as a logical development of his program. Following this vein, studies on effects of geometric properties of human relative motion using point-light displays have explored a diversity of effects on the perception of aspects such as depth (Schouten, Troje, & Verfaillie, 2011; Vanrie, Dekeyser, & Verfaillie, 2004; Vanrie & Verfaillie, 2006), viewpoint (Jokisch, Daum, & Troje, 2006), and inversion (Troje & Westhoff, 2006, Sumi, 1984), among others.

The first chapter introduces the theoretical framework and specific paradigms that have been applied to study the perception of the direction of articulatory motion of human actions depicted as point-light displays. It comprises general considerations which consist of a brief review of theoretical approaches and definitions that have shaped the topic, brief descriptions of the theoretical and experimental paradigms used in the study of biological motion perception, the statement of research questions and methodology we have used in our studies, and an overview of the dissertation.

The purpose of Chapter 2 is to investigate perception of articulatory motion in point-light figures using the simultaneous-masking paradigm with a masked (forward or backward moving) walker (signal) or a scrambled (forward or backward moving) walker (noise). We analyze sensitivity (d') as well as response bias (c).

In Chapter 3 we investigate perception of articulatory motion in different point-light actions (walking, crawling, hand walking, and rowing) presenting a forward or backward moving person to decide on the direction of articulatory motion of the person. We analyze sensitivity (d') as well as response bias (c). In addition to the type of action, the diagnosticity of the available information was manipulated by varying the visibility of the body parts (full body, only upper limbs, or only lower limbs) and the viewpoint from which the action was seen (from frontal view to sagittal view).

The goal of Chapter 4 is the introduction of a novel technique to explain sensitivity responses in psychophysical experiments as reported in Chapter 3. We summarize the main findings of our research reported in Chapter 3 and explain the need for a technique to measure the amount of asymmetry in the horizontal direction of motion of animated actions. Then we deduce four indices to measure symmetry/asymmetry of the direction of its motion and the phase portrait representation and use them to analyze asymmetry of motion of individual joints clustered by body parts and varying for orientations from profile to frontal view, for the point-light actions studied in Chapter 3.

In Chapter 5 we compare perception of forward and backward point-light walkers versus their reversed displays. We analyze sensitivity (d') measures derived from response to signal (forward/backward moving walker) and noise (reversed versions) stimuli as well as response bias (c).

Finally, in Chapter 6 we summarize empirical findings, methodological novelties, sketch future research, and make concluding remarks stressing strengths and limitations of the work.

Alex Ernesto Dávila Dávila *perceptie van de richting van beweging van articulatorische puntlicht actie-stimuli*
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Promotor: Prof. Dr. Karl Verfaillie
Co-promotor: Dr. Ben Schouten

Het waarnemen en interpreteren van de richting van menselijke bewegingen en acties is nodig om effectief en efficiënt met andere mensen te communiceren. Bijvoorbeeld, het voorspellen van de snelheid waarmee een bejaardee een boze hond vermijdt, kan zijn / haar veiligheid vergroten omdat we in staat zouden zijn om in te grijpen en een aanval te voorkomen. Vanuit een experimenteel perspectief kan de studie van de perceptie van de richting van articulatorische menselijke beweging teruggevoerd worden naar het oorspronkelijke theoretische perspectief en De onderzoeker was in staat om een stimulus te creëren die bestaat uit een aantal puntlichten die een deel van de gewrichten van een persoon vertegenwoordigen om de perceptie van menselijke beweging in laboratoriumcontexten te onderzoeken die zeer lijken op onze perceptie in het dagelijks leven: de biologische bewegingsstimulus.

Aangezien het onderhavige proefschrift betrekking heeft op een studie van de perceptie van de richting van articulatorische beweging van menselijke acties die als puntlicht-stimuli worden afgebeeld, lijkt het redelijk om Johansson's ideeën te volgen over de manier om de stimulus -gebruikende fysieke concepten te analyseren-. Na aanleiding van deze onderzoelsijn hebben studies over effecten van geometrische eigenschappen van menselijke relatieve beweging met behulp van puntlichtdisplays een verscheidenheid aan effecten op de perceptie van aspecten zoals diepte onderzocht (Schouten, Troje, & Verfaillie, 2011; Vanrie, Dekeyser, & Verfaillie, 2004; Vanrie & Verfaillie, 2006), standpunt (Jokisch, Daum, & Troje, 2006) en inversie (Troje & Westhoff, 2006; Sumi, 1984).

Het eerste hoofdstuk introduceert het theoretische kader en specifieke paradigma's die zijn toegepast om de perceptie van de richting van articulatorische beweging van menselijke acties te bestuderen Het omvat algemene overwegingen die bestaanuit een korte beoordeling van theoretische benaderingen en definities die het onderwerp hebben gevormd, korte beschrijvingen van de theoretische en experimentele paradigma's die zijn gebruikt bij het bestuderen van biologische beweging, de verklaring van onderzoeksvragen en methodologie die we in onze studies toepasten en een overzicht van het proefschrift.

Het doel van hoofdstuk 2 is het onderzoeken van perceptie van articulatorische beweging in puntlichtfiguren met behulp van het simultaanmaskeringsparadigma met een gemaskeerde (voorwaartse of achterwaartse bewegende) wandelaar (signaal) of een gecodeerde (voorwaartse of achterwaartse bewegende) wandelaar (geluid). We analyseren gevoeligheid (d ') evenals respons bias (c).

In hoofdstuk 3 onderzoeken we de perceptie van articulatorische beweging in verschillende puntlichtacties (wandelen, kruipen, handwandelen, en roeien) waarin een voorwaartse of achterwaartse bewegende persoon wordt voorgesteld om de richting van de articulatoire beweging van de persoon te bepalen. Naast het soort actie werd de diagnose van de beschikbare informatie gemanipuleerd door de zichtbaarheid van de lichaamsdelen (volledig lichaam, alleen bovenste ledematen of alleen onderste ledematen) te veranderen en het standpunt waaruit de actie werd gezien (vanaf vooraanzicht naar sagittale weergave).

Het doel van hoofdstuk 4 is de invoering van een nieuwe techniek om sensitiviteit in psychofysische experimenten te verklaren zoals gerapporteerd in hoofdstuk 3. We vatten de belangrijkste bevindingen van ons onderzoek samen dat is gerapporteerd in hoofdstuk 3 en leggen de behoefte aan een techniek om de hoeveelheid asymmetrie te meten in de horizontale bewegingsrichting van geanimeerde acties.Vervolgens leiden we vier indexen af om de symmetrie / asymmetrie van de bewegingsrichting te meten en de faseportretvoorstelling te analyseren en te gebruiken om asymmetrie van bewegingen van individuele gewrichten te analyseren die door lichaamsdelen worden geclusterd en afwijken van oriëntaties van profiel naar vooraanzicht.

In hoofdstuk 5 vergelijken we de waarneming van voorwaartse en achterwaartse puntlichtgangers tegenover hun omgekeerde displays. We analyseren gevoeligheidsmaatregelen (d ') die afkomstig zijn van respons op signaal (voorwaartse / achterwaartse bewegende wandelaar) en geluidssterkte (omgekeerde versies) stimuli, evenals responsverhouding (c).

Ten slotte vatten we in hoofdstuk 6 empirische bevindingen, methodologische nieuwigheden, schets toekomstig onderzoek samen en maken we concluderende opmerkingen die de sterkten en beperkingen van het werk beklemtonen.

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Chapter 1

Introduction

ABSTRACT

The purpose of the present chapter is to introduce the theoretical framework and paradigms that will be applied to the study of the perception of the direction of articulatory motion of human actions depicted as point-light displays. The chapter comprises: First, general considerations, second, a brief review of definitions of biological motion, perception of biological motion, and perception of the direction of articulatory motion, third, brief descriptions of theoretical and experimental paradigms used in the study of biological motion perception, fourth, the statement of research questions and methodology used in our studies, and fifth, an overview of the dissertation.

GENERAL CONSIDERATIONS

The study of the perception of the direction of articulatory human motion may be traced back to the original theoretical perspective introduced by Johansson (1973) to study perceptual organization.

Johansson when referring to our everyday experience, explains that humans distinguish among different standard types of limb motion patterns and whether any of these motions are going forwards. He writes: "We immediately see whether a person is walking, running, or dancing, and also if he is moving forward with identical speed in these three cases" (Johansson, 1973, p. 1).

As Troje (2013) has pointed out, biological motion stimuli have provided rich sources of information for the vision researcher interested on issues such as "identity of an agent as well as its actions and intentions" (Troje, 2013, p. 3). He indicates that this social significance has motivated and justified the wide interest in the topic.

Troje identifies two connections between former work of Johansson and the contemporary field of social perception: One of these connections is the technical value of Johansson type stimuli because they carry information of motion but no other visual characteristics (i.e., color and form). Another connection stressed by the author is the tight association between the term "biological motion" and the Johansson's stimulus.

There are two issues of interest to us in Johansson's contribution: First, his description of the physical properties of the animations. He writes: "Human walking, for instance, as well as the same types of motion in most domestic animals can readily be

described as combinations of several pendulum-like motions of the extremities relative to a joint" (Johansson, 1973, p. 201), and second, his program. He asserts: "The present study is the first in a planned series of investigations on perception of such rather complex patterns of live motion and their outcome in body displacement" (Johansson, 1973, p. 201).

As the present dissertation deals with a study of perception of the direction of articulatory motion of human actions depicted as point-light displays, it seems reasonable to follow Johansson's ideas about the way to analyze the stimulus –using physical concepts- and the kind of research he expected to have as a logical development of his program. Following this vein, studies on effects of geometric properties of human relative motion using point-light displays have explored a diversity of effects on perception such as depth (Schouten, Troje, & Verfaillie, 2011; Vanrie, Dekeyser, & Verfaillie, 2004; Vanrie & Verfaillie, 2006), viewpoint (Jokisch, Daum, & Troje, 2006), and inversion (Troje & Westhoff, 2006, Sumi, 1984), among others.

Perception of the direction of articulatory motion of a walker moving on a treadmill (relative motion) has been specifically studied in human observers (e.g. Cutting 1981; Cutting & Proffitt, 1981; Kuhlmann, de Lussanet & Lappe, 2009; Lu & Liu, 2006; Verfaillie, 1993; Verfaillie, 2000; Wittinghofer, de Lussanet, & Lappe, 2012) as well as in macaques (e.g. Vangeneugden, Vancleef, Jaeggli, Van Gool & Vogels, 2010).

DEFINITIONS

What follows is a set of definitions to be used in our work:

Biological motion. Troje (2013, p. 4) defines biological motion as "stimuli and studies concerned with the intrinsic, non-rigid motion of the deforming body, rather than the motion path that its centre of gravity subscribes through space". This definition stresses the higher frequency of studies using non-translational and relative motion of different body parts in the biological motion literature. An issue of interest in biological motion research is the use of different kinds of stimuli: Under the umbrella of the previous definition, it is possible to have biological motion animations made for instance of point-light displays, avatars, or stick figures. Even biological motion of human actors captured by video may be used as stimulus. Troje indicates that point-light displays are more convenient for reconstruction of structure from motion and stick figures more convenient for identification of the semantic content of the figure (i.e., recognition of an action). As our point of interest is perception of direction of articulatory motion, we may assert that point-light displays will be the most convenient stimuli for our study.

Perception of biological motion. We will focus on *visual* perception of biological motion. Visual perception of human motion is understood as the sensitivity to detect and interpret human motion in point-light displays "even under impoverished or potentially ambiguous conditions" (Blake & Shiffrar, 2007, p. 51).

Perception of the direction of articulatory motion. Within the context of our research, we focus on the perception of the direction of articulatory motion. In the case of a sagittal view, these directions may be "forward" or "backward", the specific geometric sense of "forward" or "backward" will be determined in correspondence with the facing orientation of the animation: If the orientation is to the left, "forward" direction will be to the left, and "backward" direction to the right. If the orientation is to the right, "forward" direction will be to the right and "backward" to the left. Articulatory motion means movement without translation of a body whose parts are articulated by joints. In the case of studies of human biological perception, body may refer to the footage of a human body in video, an avatar, a stick figure, or a point-light set.

THEORETICAL AND EXPERIMENTAL PARADIGMS

There is a diversity of theoretical and experimental paradigms to study the perception of biological motion. What follows is a brief review of several paradigms. We organize our review according to the broad research field to which specific paradigms have been historically more associated. When available, we will refer to findings on the perception of the direction of articulation.

Psychophysics. Here we focus our brief review on two paradigms: threshold detection and signal detection theory (SDT). Threshold detection was developed as a paradigm by Gustav Fechner (1801-1897) who is credited as the father of psychophysics and one of the founders of experimental psychology. Contemporary research on the perception of biological motion includes the use of procedures such as threshold estimation (e.g. Koldewyn, Whitney, & Rivera, 2011; Tyler & Grossman, 2011) and adaptive thresholding (e.g. Miller & Saygin, 2013; Gold, Tadin, Cook, & Blake, 2008). SDT was applied to psychophysics for the first time by Marill (1956) for the design and analysis of results in auditory experiments using forced-choice responses to detect signals masked by Gaussian noise. SDT has been used in contemporary perception of biological motion research by Bertenthal and Pinto (1994) to detect point-light displays masked by additional point-lights. It led to the development of the theoretical concept of "ideal detector" and the derivation of a psychophysical function for it. In practical terms, SDT is a very useful approach because

it considers both right and wrong detections of target and non-target stimuli of interest (i.e., biological and non-biological motion). We must turn now our attention to the paradigms that have been used to study perception of biological motion.

Perception. Troje (2013, p. 5) asserts: "In trying to bring some order to the large host of literature, a reasonable distinction is the one between studies that aim to assess biological motion perception in general, and the ones that ask very specific questions about what kind of information can be retrieved from biological motion stimuli.". The author distinguishes between detection and direction studies on the one hand and style studies on the other hand. While the former focus on mechanisms of perception to understand the kinematics and other physical properties of a point-light display, the latter pay attention to higher cognition issues such as gender identification, identity of point-light actors, performed actions, among others. In contrast with the "detection and direction" line, the "style line" may include the use of several types of animations that carry more information than point-lights (i.e., stick figures or bipeds). In both lines of research, a considerable effort has been made to design, implement, and control sophisticated animations of human biological motion (see for instance Vanrie & Verfaillie, 2004; Saunders, Suchan, & Troje, 2009); however "the detection and direction" line and "the style line" when first encountered, diverged in their perspectives to deal with the stimulus: While the "detection and direction" line is naturally interlaced and has strong epistemological and theoretical links with psychophysics, the "style" line is centered on the understanding of high level visual perception or even social perception as in the case of social cognition. In social cognition research using point-light displays, for instance, manipulation and control of detailed physical properties of the stimulus are necessary to run highly controlled sophisticated experiments. However, detailed physical properties of stimuli may be irrelevant to explain social behaviour. Then, the "style" line is a broad field in which research interests may vary from topics that qualify as visual perception (i.e., visual stimuli properties that may influence gender identification) to social cognition research (i.e., perception of intentions) among other trends. As a continuation of the former theoretical debate in the history of psychology between direct and indirect perception perspectives, nowadays a current debate holds in cognitive science on the causality direction (bottom-up vs. top-down) of processes that drive perception of biological motion. For instance, Thornton (2013, p. 25) asserts that "Bottom-up processing, then appears to be a plausible route through which the human visual system might approach the perception of point-light figures. Indeed, I would suggest that it remains the dominant or at least "popular" view of how biological motion is processed". He pays attention to Giese and

Poggio (2003) contribution as an example of a purely bottom-up model and stresses its explanatory power to account for a diversity of psychophysical data by proposing mechanisms derived from the functional properties of the dorsal and ventral visual pathways. Then the author makes the case for top-down processing in biological motion perception based on several lines of evidence (see Thornton, 2013), such as robustness of biological motion detection despite the variety of ways how it has been displayed in experiments, performance of näive observers who ideally must be unfamiliar to biological motion tasks and stimuli and must have no expectation of human motion being not the case in real experimentation, categorical perception of "chimeric" and bistable point-light walkers, among others. Finally, the author proposes a conceptual synthesis of current biological motion processing understanding: He includes in his theoretical proposal bottom-up and top-down factors and stresses attention and amodal coding as pre-requisites for the latter. What follows is a brief description of a field whose developments look promising to enrich and eventually may help to solve current debates on the causality direction of perceptual processes, particularly those linked to biological motion perception.

Perception and action. The study of the interplay between perception and action is an emerging field whose epistemological roots may be traced back to inspirational theoretical approaches such as Gibson's theory of visual perception. Gibson suggested (as cited in Hochberg, 1994, p. 161) that information "becomes available, therefore, through the interaction of the perceiver and the environment". Hochberg (1994, p. 161) indicates: "But Gibson's affordances are not mental structures. They are optical structures of information about the environment, structures that exist objectively but that must be defined in terms of the needs and potential behaviors of the individual animal". Gibson's theory is an example of direct perception theory. Turvey and Shaw assert (as cited in Michaels & Carello, 1981, p. 14): "In the ecological approach, the dualism of animal and environment is rejected. Because the study of direct perception is the study of an animal knowing its environmental niche, it is suggested that perception must be the study of an animal-environment system". Paying attention to the contribution of motoric experience to the shaping of biological motion perception, Blake and Shiffrar (2007, p. 56) write: "Converging lines of evidence strongly suggest that our keen ability to perceive the actions of other people results, in part, from the massive experience we have accumulated over the years in planning and executing self-produced activities". The authors summarize three lines of evidence on motoric contributions to perception of human motion: First, observer's own activities influence on observer's perception of the activities of other people, second, observers demonstrate maximum

sensitivity to actions most familiar to them and reduced sensitivity to actions unfamiliar to them, and third, studies of patients with disorders that affect proprioceptive mechanisms and/or motor behavior demonstrate that the ability to represent executable actions constrains the ability to perceptually interpret similar actions performed by others. In the case of perception of biological motion and actions, there is evidence for the influence of previous motor training on biological motion perception (Casile & Giese, 2006), motor familiarity on observation of dance (Calvo-Merino, Grèzes, Glaser, Passingham, & Haggard, 2006) and modulation of perception by action (Schütz-Bosbach & Prinz, 2007).

Movement science. The field of (human) movement science is closely related to the field of biomechanics and kinesiology but broader (a history of the field may be reviewed in Latash, 2009). Here we quote a description of the goals of a journal in the field: "Human movement Science provides a medium for publishing disciplinary and multidisciplinary studies on human movement. It brings together psychological, biomechanical and neurophysiological research on the control, organization and learning of human movement, including the perceptual support of movement." ("Human Movement Science", 2015). Movement science might be relevant for studies of the perception of biological motion as it approaches the study of human motion by physical descriptions at two levels: kinematics and kinetics. Kinematics describes human motion in terms of variables such as position, speed, and acceleration, and kinetics adds to the former, the study of the physical causes of motion: forces and torques.

Cognitive neuroscience. Sarter, Berntson, and Cacioppo (1996, p. 13) wrote: "While research in cognitive neuroscience combines many levels of neuroscientific and psychological analyses, modern imaging techniques that monitor brain activity during behavioral or cognitive operations have significantly contributed to the emergence of this discipline". Several studies have been made in the human and macaque to describe the neural correlates of the perception of biological motion (see Vanrie, 2005 and Schouten, 2010 for details of previous reviews in dissertations devoted to the study of biological motion perception).

Brain imaging fMRI studies in humans have taken place in neuroscience research to localize brain functions associated to biological motion perception (See for instance, Gilaie-Dotan, Kanai, Bahrami, Rees, & Saygin, 2013; Grossman & Blake, 2002; Saygin, Wilson, Hagler, Bates, & Sereno, 2004; Thompson & Baccus, 2012; Vaina, Solomon, Chowdhury, Sinha, & Bellieveau, 2001). More recently, human EEG studies aimed to find electrophysiological markers of biological motion perception have also been published

(Krakowski, Ross, Snyder, Sehatpour, Kelly, & Foxe, 2011; Saunier, et al., 2013; White, Fawcett, & Newman, 2013). The fMRI technique has as a limitation its lack of temporal resolution and EEG techniques based on recording of scalp potentials provide electrophysiological data that do not correspond directly to local field potentials originated from cortical and sub-cortical sources. Elucidation in a future of the precise topographical and temporal correspondence of biological motion perception with neural localization and activity, would increase the understanding of the contributions of the visual system, the mirror neuron system, and other neural systems that have been proposed or eventually will be proposed as foundations or correlates of biological motion perception.

In the case of the visual system the current debate lies on the contribution of the dorsal and ventral visual pathways to biological motion perception. For instance, Thompson and Baccus (2012) found using fMRI that form and motion features of the stimuli explained responses toward biological motion in lateral occipitotemporal regions MT, MST, and the extrastriate body area. Another example is the article of Mather, Battaglini, and Campana (2016) who concluded after using TMS stimulation over MT+/V5 during the execution of a coherent motion perception and a biological motion perception tasks, that MT+/V5 is needed in the processing of simple coherent motion but not in the processing of biological motion: As MT+/V5 belongs to the dorsal pathway, their findings would reveal a flexible use of form and motion cues during the execution of the tasks.

Mirror neurons were discovered first in area F5 of the macaque using sincle cell recording techniques (Rizzolatti, Fadiga, Gallese, & Fogassi, 1996). The novelty of this finding was that F5 neurons fire when the monkey performs an action or when he observes a similar action made by another monkey or by the experimenter. In a posterior communication, Rizzolatti, Fogassi, & Gallese (2001) highlighted another discovery made by Perret et al. (1985) also in the macaque and using single cell recording: The firing of neurons of the anterior superior temporal sulcus (STSa) when the monkey observes biological action. In the same article where the F5 findings were communicated, Rizzolatti et al. (2001) reported the activation of neurons localized in the human inferior gyrus (Broca's area). Rizzolatti and Craighero (2004) reported in a posterior contribution their review of available evidence at that time and suggested that the core of the human mirror neuron system is the rostral part of the inferior parietal lobule and the lower part of the precentral gyrus plus the posterior part of the inferior frontal gyrus. In a more recent review and synthesis, Rizzolatti, Cattaneo, Fabbri-Destro, and Rozzi (2014) assert that the mirror

mechanism is located in parietal and frontal areas and is involved in understanding the action and intention of others.

RESEARCH QUESTIONS AND METHODOLOGY

As we have described above, the purpose of this dissertation is the study of the perception of the direction of articulatory human motion using point-light displays.

A first set of questions of interest is about performance and biases towards forward walking. To answer these questions we will adapt the simultaneous-masking paradigm procedure using normal displays (forward or backward) and their scrambled versions for the action of walking. We will calculate SDT measures of sensitivity and response bias using responses to these animations. Based on the existence of motoric influences on biological motion perception (Casile & Giese, 2006, Calvo-Merino et al., 2006), we expect higher sensitivity and bias when the original animation is going forwards than when it is going backwards (actually this "backward" display will be the reversal of the forward animation).

As the simultaneous-masking paradigm procedure uses masks of moving dots (Cutting, Moore, & Morrison, 1988), a secondary set of questions deals with expected performance for different amounts of moving dots used as masks (noise): In this case higher sensitivity when each original animation (without considering if it is a forward or a backward display) and their scrambled displays are masked by few dots.

A second set of questions of interest is about the factors that may determine perceptual differences in response to forward and backward point-light displays. To answer the first question of this set, we turn our attention to body parts: As it has been reported before that information on direction of articulated motion is mainly carried by the motion of the ankle (Saunders et al., 2009), we will display in sagittal view the whole point-light walker going either forwards or backwards, or part of it (lower or upper body part). We expect higher sensitivity in the full and lower display conditions than in the upper condition. Further questions of this set will include different viewpoints (from saggital to frontal views) and different actions. In all cases we predict higher sensitivity for results correspondent to the full body and the body part that might be more informative (for instance, in the case of hand walking, the informative part would be the upper part of the body).

A third set of questions of interest is about the possibility of using kinematic information of animations to explain results for the second set of questions. We will explore if speed, acceleration or a mathematical concept that combines them (phase portrait)

correspondent to individual dots, body parts or viewpoints, explain sensitivity results for the actions that will be studied to answer the second set of questions.

A final set of questions is focused on exploratory comparisons between performance responses towards forward walking and real backward walking (not reversed displays of forward walking). We calculate sensitivity and bias correspondent to forward walking and real backward walking.

OVERVIEW OF THE DISSERTATION

The purpose of Chapter 2 is to investigate perception of articulatory motion in point-light figures using the simultaneous-masking paradigm with a masked (forward or backward moving) walker (signal) or a scrambled (forward or backward moving) walker (noise). We analyze sensitivity (d') as well as response bias (c).

In Chapter 3 we investigate perception of articulatory motion in different point-light actions (walking, crawling, hand walking, and rowing) presenting a forward or backward moving person to decide on the direction of articulatory motion of the person. We analyze sensitivity (d') as well as response bias (c). In addition to the type of action, the diagnosticity of the available information was manipulated by varying the visibility of the body parts (full body, only upper limbs, or only lower limbs) and the viewpoint from which the action was seen (from frontal view to sagittal view).

The goal of Chapter 4 is the introduction of a novel technique to explain sensitivity responses in psychophysical experiments as reported in Chapter 3. We summarize the main findings of our research reported in Chapter 3 and explain the need for a technique to measure the amount of asymmetry in the horizontal direction of motion of animated actions. Then we deduce four indices to measure symmetry/asymmetry of the direction of its motion and the phase portrait representation and use them to analyze asymmetry of motion of individual joints clustered by body parts and varying for orientations from profile to frontal view, for the point-light actions studied in Chapter 3.

In Chapter 5 we compare perception of forward and backward point-light walkers versus their reversed displays. We analyze sensitivity (d') measures derived from response to signal (forward/backward moving walker) and noise (reversed versions) stimuli as well as response bias (c).

Finally, in Chapter 6 we summarize empirical findings, methodological novelties, sketch future research, and make concluding remarks stressing strengths and limitations of the work.

Chapter 2

Perception of the direction of articulation of walking: the simultaneous masking-paradigm

ABSTRACT

Human observers are able to perceive the direction of motion (either forwards or backwards) on the basis of the articulatory, relative motion of the limbs, even when the action is shown as a point-light stimulus. The purpose of the present study is to investigate perception of the direction of articulatory motion in point-light figures using the simultaneous-masking paradigm. On each trial, participants were presented with a masked (forward or backward moving) walker (signal) or a scrambled (forward or backward moving) walker (noise) and they had to decide on the presence of the signal or noise walker. We analyzed sensitivity (d') as well as response bias (c). We failed to observe a statistically significant effect of direction of articulation on the detection of a point-light walker in a simultaneous-masking paradigm.

INTRODUCTION

Accurate perception and understanding of the actions and intentions of conspecifics is a crucial prerequisite for adequate social interaction (Gallese, Keysers, & Rizzolatti, 2004; Manera, Becchio, Schouten, Bara, & Verfaillie, 2011). A remarkable demonstration of this ability is the perception of point-light actions (Johansson, 1973): A handful of point lights attached to strategic positions on the body of a moving human body is sufficient to allow the observer to pick up several behaviorally relevant properties both of the moving person and of the action performed.

One aspect that has received attention in the literature of biological motion perception, both in human observers as well as in nonhuman primates, is the perception of the direction of walking (forward vs. backward) of a human figure moving as if on a treadmill. For instance, in a study of Verfaillie (1993), participants had to discriminate between a normal walker point-light display and a similar distractor. The point-light walker was facing either to the right or to the left and walking either forward or backward. Forward walking figures were identified significantly faster than backward walking figures (Note that the walking direction was task irrelevant in this study). The author stresses that the difference between the perception of a human and a nonhuman walker has to do with the spatial structure of the objects, not with the particular action they are involved in (participants were instructed to discriminate between two objects, irrespective of the way they were moving).

In a follow-up study (Verfaillie, 2000) participants had to discriminate between forward and backward walking figures (making perception of walking direction task relevant). Latencies to forward walking displays were again shorter than to backward walking displays but the difference was not statistically significant.

The primary aim of the present study was to investigate the perception of the direction of forward or backward articulatory motion in point-light walkers using a simultaneous-masking paradigm (e.g., Bertenthal & Pinto, 1994; Cutting et al., 1988; Thornton, Pinto, & Shiffrar, 1998) with a limited-lifetime technique and scrambled distractors (see Neri, Morrone, & Burr, 1998).

Thornton et al. (1998) found decreased discrimination performance when local motion processing cues were removed for a profile full body point-light figure as if on a treadmill. In their experiment, the figure was in profile view, walked to the right or to the left and was embedded in a background of noise which consisted of a scrambled walker mask. In posterior research, Beintema and Lappe (2002) reported that addition of local motion signals by increasing the number of limited-lifetime points improved detection performance for a profile walker against a random noise background of points and the same authors indicate in a posterior communication that the order of displayed frames which distinguishes normal from scrambling walking is relevant in biological motion discrimination tasks because it provides a cue to solve these tasks (Beintema & Lappe, 2006).

We tested the hypothesis that the detection of a forward articulating point-light walker and detection of its correspondent scrambled distractor is greater than the detection of a backward articulating point-light walker and its distractor: It was of interest to prove if the detection elicited by the forward point-light figure might be more efficient than the detection elicited by the backward point-light figure combining the limited-lifetime technique and the using or random noise masks. We took into account that both forward and backward walking have the same kinematic properties with the exception of their directions of motion that are opposite. Maybe, this property, suffices to produce differences in detection under our experimental conditions.

As our signal (a forward or backward normal walker) and the noise (their correspondent scrambled walkers) were embedded within clouds of random moving dots, we also expected sensitivity to decrease as the amount of noise dots increases and bias to remain the same across noise conditions.

EXPERIMENT

METHOD

Participants. 21 students of psychology at the KUL (19 women, 2 men, M_{age} = 19.16 years, SD_{age}= 2.43 years) participated in this experiment for course credit. All observers had normal or corrected to normal vision and were naive to the purpose of the experiment. The study was approved by the Ethical Committee of the Faculty of Psychology and Educational Sciences of the University of Leuven and in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki. Participants provided written informed consent (following the consent procedure approved by the Ethical Committee). One participant was under 18 (age 17.98). For this participant we did not obtain consent from their parents or legal guardians, because the Ethical Committee of our faculty urges this only for participants under the age of 16.

Stimulus. There were two forward stimuli: The signal which consisted of a point-light human walker in profile orientation going forwards and facing to the left. This moving figure was designed using motion capture data from a real walker and a 3D animation technique (Dekeyser, Verfaillie, & Vanrie, 2002; Vanrie & Verfaillie, 2004) and consisted of 90 still images or frames. The animation was played with MATLAB for Windows XP with a frame refreshing rate of 60 Hz on the screen of a Dell monitor starting randomly at any of the 90 images and appearing at random positions within the central display area of the monitor on a trial-by-trial basis. This yielded a walking velocity of about 1.34 steps each second, speed that corresponds to about 80 steps per minute, value within the range of normal walking for healthy adults (Dall, McCrorie, Granat, & Stansfield, 2013). Each image consisted of 13 white dots positioned on the major joints of the walker (the head, two shoulders, two elbows, two wrists, two hips, two knees, and two ankles; radius = 3 pixels) on a gray background.

Only 6 of the 13 dots were chosen randomly from each frame (6 signal dots). Once a dot was chosen from a frame, it was available to be depicted at that frame and the next 11 frames in the animated sequence (12 frames alive; see Neri et al., 1998), then disappeared, and reappeared at another location randomly chosen from the 7 still available locations. Dot appearance and disappearance were asynchronous across frames in order to avoid visible motion transients from simultaneous transitions of all dots.

The noise consisted of a point-light scrambled walker that had, across its time of display, equal average positions of its dots compared to the average positions of the dots of

the point-light normal forward walker (the signal) from which it was derived. However, while the signal display (normal walker) carried the original relative temporal relations among dots, in the noise stimulus (scrambled walker) the relative temporal relations were randomized (see Neri, Luu, & Levi, 2006). The signal and the noise backward stimuli were identical to their forward counterparts but in comparison with them, they were played in reverse. Both the signal and the noise stimuli were embedded within masks made of 30, 20 or 10 points moving randomly within a defined rectangular region where the signal or noise point-light walkers appeared.

Procedure. The experiment was run in a dimly lit and sound-attenuated lab room. The participants were instructed first and practiced to press the up '↑' button on the keyboard when they perceived an animation as signal and the '↓' button when they perceived an animation as noise. After this practice, forward and backward stimuli were presented in 16 separate blocks (8 with forward and 8 with backward walkers and their correspondent distractors). Each individual stimulus lasted 1.5 sec. Both sequence of blocks and sequence of trials within each block were randomized. Each block of trials contained 5 repetitions/condition in 6 conditions (signal or noise trials x 3 noise levels) resulting in 30 trials/block. We analyzed sensitivity (d') as well as response bias (c) measures.

RESULTS

Values of d' (Figure 1) were analyzed using a repeated measures two-way analysis of variance (ANOVA) having as within-subjects factors the direction of articulation (going either forwards or backwards) and the amount of noise (30 dots, 20 dots, and 10 dots). The Mauchly's test indicated that the assumption of sphericity for the amount of noise had been violated ($\chi 2(2) = 9.948$, $p < .01$). Therefore degrees of freedom for this factor were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = 0.749$). The ANOVA yielded no significant main effect of direction of motion, $F(1, 20) = 0.590$. As expected, there was a significant main effect of amount of noise, $F(1.42, 28.42) = 13.85$, $p < .001$. Planned comparisons showed d' for 30 noise conditions ($M = -0.276$, $SD = 0.458$) < d' for 20 noise conditions ($M = 0.016$, $SD = 0.393$), $p < .01$ and d' for 20 noise conditions ($M = 0.016$, $SD = 0.393$) < d' for 10 noise conditions ($M = 0.402$, $SD = 0.615$), $p < .01$.

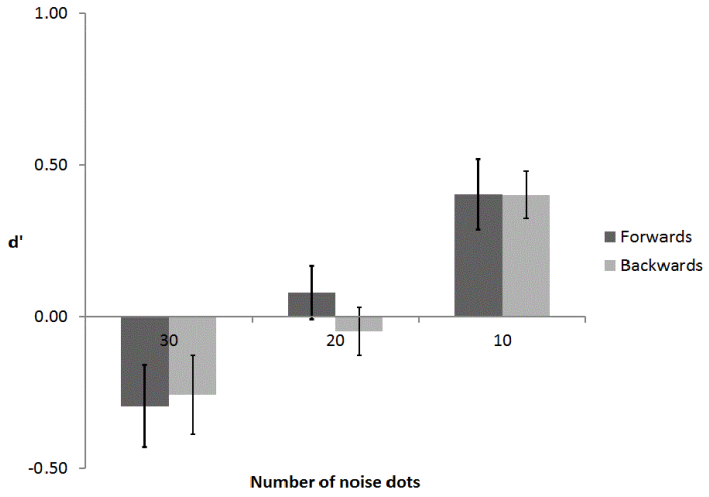

Figure 1. **d' (including standard error bars) as a function of direction of articulation and noise level.**

A similar ANOVA on c yielded no significant main effect of direction of articulation, $F(1, 20) = 0.222$. There was a significant main effect of amount of noise, $F(2, 40) = 35.173$, $p < .001$ (Figure 2): Participants were more likely to respond that a normal walker was present than a distractor for lower noise levels.

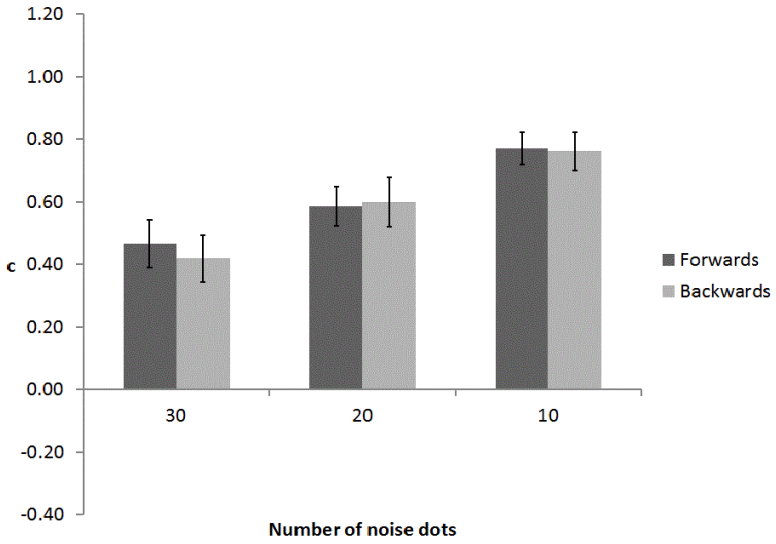

Figure 2. **c (including standard error bars) as a function of direction of articulation and noise level.**

DISCUSSION

In this experiment, we failed to observe a statistically significant effect of direction of articulation on the detection of a point-light walker in a simultaneous-masking paradigm. In contrast with the experiment reported by Beintema and Lappe (2002) who also used random moving dots to mask limited-lifetime point-light walkers moving to the right or to the left in a direction discrimination task, we found that detection of normal walking figures against their distractors did not differ. Moreover, in our experiment performance both for the forward and the backward detection tasks was poor (see Figure 1) and probably impoverished alike by the masking conditions.

Our findings showing increasing sensitivity for both forward and backward detection in function of decreasing number of dots of the random mask, would be explained as follows: As in our experiment we combined the limited-lifetime technique and the using of random masks with different number of dots, it might be the case that local motion cues were available but did not suffice to have a differential effect on the task of detection of normal and scrambled walkers going forward and backward against their distractors even with 12 frames alive. Precisely Thornton et al. (1998) introduced the using of scrambled walker masks to cancel local motion differences between the dots that comprise the point-light animation and the dots that would comprise a random mask. In our experiment, however, these local effects may seem have been ineffective as cues for the detection.

In this experiment we found that participants were more likely to respond that a normal walker was present than a distractor for lower noise levels: As the masking conditions affected this response, it might be the case that local motion information was not available at the same magnitude for expression of bias. We also found that bias for the forward and the backward detection tasks was similar across the noise conditions (see Figure 2).

Finally, we may conclude that it is possible that detection of a point-light walker is not affected by the direction of articulation if the full body is shown when a simultaneous-masking paradigm is used. Alternatively, maybe this paradigm is not optimally suited to tackle the question when the signal and noise detection task includes the using of normal and scrambled walkers embedded in random masks.

Chapter 3

Perception of the direction of articulatory motion of point-light figures

This chapter is based on:

Davila, A., Schouten, B., & Verfaillie, K. (2014). Perceiving the direction or articulatory motion in point-light actions. *PLoS ONE, 9*(12): e115117. doi:10.1371/journal.pone.0115117

ABSTRACT

Human observers are able to perceive the motion direction of actions (either forwards or backwards) on the basis of the articulatory, relative motion of the limbs, even when the actions are shown under point-light conditions, but most studies have focused on the action of walking. The purpose of the present study is to further investigate perception of articulatory motion in different point-light actions (walking, crawling, hand walking, and rowing). On each trial, participants were presented with a forward or backward moving person and they had to decide on the direction of articulatory motion of the person. We analyzed sensitivity (d') as well as response bias (c). In addition to the type of action, the diagnosticity of the available information was manipulated by varying the visibility of the body parts (full body, only upper limbs, or only lower limbs) and the viewpoint from which the action was seen (from frontal view to sagittal view). We observe that, depending on the specific action, perception of direction of motion is driven by different body parts. Implications for the possible existence of a life detector, i.e., an evolutionarily old and innate visual filter that is tuned to quickly and automatically detect the presence of a moving living organism and direct attention to it, are discussed.

INTRODUCTION

The Leuven psychologist Albert Michotte, a pioneer in research on the perception of animate motion, pointed out already several decades ago that "a thorough study of behaviour must take into account the way in which people and animals 'understand' the actions of other people and animals, as well as those they perform themselves" (Michotte, 1954/1991, p. 34) Indeed, accurate perception and understanding of the actions and intentions of conspecifics is a crucial prerequisite for adequate social interaction (Gallese et al., 2004; Manera et al., 2011). A remarkable demonstration of this ability is the perception of point-light actions (Johansson, 1973): A handful of point lights attached to strategic positions on the body of a moving human body is sufficient to allow the observer to pick up several behaviorally relevant properties both of the moving person and of the action performed (see Blake & Shiffrar, 2007; Giese & Poggio, 2003; Thompson & Parasuraman, 2012; Verfaillie, 2000 for

reviews and some historical background; note that, in his seminal paper on biological motion perception, Johansson refers to Michotte's work on the perception of animate motion: "Stimulus patterns representing animals in motion have been rarely studied. Michotte's [1963; originally published in 1946] study of perception of larva motion may be pointed to as an important exception" (Johansson, 1973, p. 201)).

Although it has been documented repeatedly that human observers easily identify different types of human (inter)actions under point-light conditions (e.g., Dittrich, 1993; Manera, Schouten, Becchio, Bara, & Verfaillie, 2010; van Boxtel & Lu, 2011; Vanrie & Verfaillie, 2004), most studies of biological motion perception focused on the perception of human walking. One aspect that has received attention in the literature is the perception of the direction of walking (forward vs. backward) of a walker moving on a treadmill, in human observers (e.g., Kuhlmann et al., 2009; Lange & Lappe, 2007; Lu & Liu, 2006; Saunders, Williamson, & Troje, 2010; Verfaillie, 2000), as well as in nonhuman primates (Vangeneugden et al., 2010). With this stimulus configuration the global translatory component of motion (common motion) is set to zero and discrimination of the direction of motion can only be based on the articulatory movements of the body parts in relation to each other (relative motion; e.g., Cutting, 1981; Cutting & Proffitt, 1981).

For instance, in a study of Verfaillie (1993), participants had to discriminate between a biological motion walker and a similar distractor. The point-light walker was facing either to the right or to the left and walking either forward or backward. Forward walking figures were identified faster than backward walking figures. (Note that the walking direction was task irrelevant in this study). In a follow-up study (Verfaillie, 2000) participants had to discriminate between forward and backward walking figures (making perception of walking direction task relevant). Latencies to forward walking displays were again shorter than to backward walking displays (but the difference was not statistically significant).

There are several possible, not necessarily mutually exclusive, reasons to speculate why backward walking might be more difficult to perceive and interpret than forward walking. First, human observers are relatively rarely confronted with backward moving walkers, so familiarity might play a role. It has indeed been suggested repeatedly that stored knowledge of actions (or the identity of the actor) play a pivotal role in action and posture perception (e.g., Bülthoff, Bülthoff, & Sinha, 1998; Cavanagh, Lablanca, & Thornton, 2001; McBeath, Morikawa, & Kaiser, 1992; Vanrie & Verfaillie, 2006). Second, the anatomy of the human body probably is not optimally suited for backward walking. Under the assumption that motor knowledge influences visual perception of human movements (e.g.,

Casile & Giese, 2006; Manera et al., 2012; Schütz-Bosbach & Prinz, 2007; Wilson & Knoblich, 2005), perception of backward movement might therefore be compromised.

The primary aim of the present study is to further investigate the perception of the direction of motion (either forwards or backwards) on the basis of the articulatory, relative motion of the limbs, not only when observers view a walking action but also when perceiving other actions. More specifically, perception of the direction of articulatory motion is studied in walking, crawling, hand walking, and rowing. We use a signal detection paradigm. On each trial, participants are presented with a forward (signal) or backward (noise) moving person and they have to decide on the direction of articulatory motion of the person. We analyze sensitivity (d') as well as response bias (c).

One obvious (and the most important for the present examination) reason for studying direction of motion perception not only when observers view a walking action but also when perceiving other actions has to do with generalizability from findings on walking to other actions. However, in addition to that, there are other, more theoretical, reasons. The perception of the direction of walking probably is mainly driven by the movement of the extremities of the moving human body, especially the movement of the feet. Troje and colleagues even have suggested (Chang & Troje, 2008, Chang & Troje, 2009a; Chang & Troje, 2009b; Schouten et al., 2011; Saunders et al., 2009; Troje & Westhoff, 2006) that during the perception of human locomotion a specialized life detector mechanism is activated, an evolutionarily old and innate visual filter that is tuned to quickly and automatically detect the presence of a moving living organism and direct attention to it. In fact, Michotte (1954) already alluded to this possibility: "les mouvements exécutés par l'homme ou l'animal possèdent un caractère special qui les différencie nettement, d'ordinaire, des mouvements des objects inanimés, et qui permet de reconnâitre aisément la présence d'une vie animale, fait capitale au point de vue biologique (the movements performed by men or animals have a special nature that differentiates them clearly from the movements of inanimate objects and that allow effortless recognition of the presence of animate life, an important fact from a biological point of view)".

Because of the presence of gravitational forces, perceived acceleration patterns in the movements of the feet during walking play a prominent role in this process. Research on the perception of the articulatory direction of motion, also in other actions than walking, might lead to a better understanding of this life detector.

Given the evolution of the human species towards upright, bipedal, walking, it is perhaps not surprising that perception of motion direction indeed probably is mainly driven

by the movements of the lower limbs during the perception of most common forms of human locomotion. However, for other, less common, locomotion styles, it can be expected that the upper limbs also carry important information. In Experiments 1 and 2, participants viewed the traditionally studied action of walking, in which motion of the limbs probably is most diagnostic for direction discrimination. In Experiment 3, observers were presented with a crawling action (MacLellan, Ivanenko, Cappellini, Sylos Labini, & Lacquaniti, 2012; Patrick, Noah, & Yang, 2012; Withagen & Michaels, 2002). It can be expected that, even though the action is uncommon, for this quadruped mode of locomotion both lower and upper limbs carry information of the direction of articulatory motion. In Experiment 4, we showed subjects an even less familiar action, namely hand walking (Shipley, 2003), in which the movements of the arms probably are most diagnostic (and the legs carry no useful information). The action stimulus in Experiment 5 consisted of a rowing action. In contrast to the intransitive (i.e., no accessory devices are necessary for locomotion) actions of walking, crawling, and hand walking, rowing is a transitive action (i.e., motion is realized not by direct contact of the limbs with the ground surface, but indirectly by making use of locomotory tools like a boat). In the case of rowing, direction of articulatory motion probably mainly is signaled by the movements of the upper limbs.

Apart from varying the type of action, a second way in which we manipulated the diagnosticity of different body parts simply consisted of restricting the available stimulus information either to the upper limbs or the lower limbs (in comparison to a control condition in which the full body was presented) for the different types of actions (see Takahash et al., 2011 for related research on the role of different body parts in direction discrimination of point-light actions).

Thirdly, perception of movement direction probably varies with the viewpoint from which the point-light stimulus is seen. For instance, the profile orientation of a walker is likely to carry more information than the frontal orientation of a walker. Kuhlmann et al. (2009) reported research on the perception of point-light limited-lifetime full body human walkers going either backwards or forwards and shown in different orientations and observed that walking direction could be readily seen in profile and half-profile views, but direction discrimination became very difficult in frontal views.

In sum, we predict that sensitivity to perceive direction of motion depends on the perceived action, the perceivable body part, and the viewpoint from which the action is seen. We also analyzed response bias, but predictions are less straightforward here. A bias for forward motion when the uncertainty about the direction of motion is increased could be

predicted. Indeed, under the latter circumstances observers might be prompted to perceive forward motion (if familiarity and/or motor knowledge influence perception of direction of articulation). In Bayesian terms, the perceptual system integrates available sensory evidence with expectations about the state of the external environment priors (Kersten, Mamassian, & Yuille, 2004; Manera et al., 2011; Sterzer, Frith, & Petrovic, 2008; Yuille & Kersten, 2006). Prior expectations (e.g., on the basis of familiarity) are expected to bias observer's performance especially when stimulus-driven processing is made more difficult (i.e., by manipulating the figure's in-depth orientation and visible body part).

EXPERIMENT 1

In Experiment 1 we focused on the perception of walking. On each trial, participants were presented with a sagittal 0° view of a point-light walker, facing to the left. (Viewpoint was not yet manipulated in Experiment 1.) They pressed one button when they perceived the figure as walking forward and another button when they perceived the walker as walking backward. Under the assumption that walking direction is carried primarily by information in the lower part of the body, we predicted that performance would be worst when only the upper part of the body was visible and that performance in the condition in which only the diagnostic lower part was visible wouldn't differ much from the full-body condition.

METHOD

Participants. 14 students of psychology at the University of Leuven (KULeuven) (13 women, 1 man, M_{age} = 18.78 years, SD_{age} = 1.03 years) participated in this experiment. All observers had normal or corrected to normal vision and were naive to the purpose of the experiment. The study (and all other experiments reported in the present chapter) was approved by the Ethical Committee of the Faculty of Psychology and Educational Sciences of the University of Leuven and in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki. Participants provided written informed consent (following the consent procedure approved by the Ethical Committee). A few participants were under 18: 1 participant in Experiment 1 (age 17.78), 1 participant in Experiment 3 (age 17.83), and 1 participant in Experiment 5 (age 17.90). For these participants we did not obtain consent from their parents or legal guardians, because the Ethical Committee of our faculty urges this only for participants under the age of 16. Just before the beginning of the experiment, written instructions were given and practice took place to make sure that participants understood the task and were well prepared for the main task.

Stimulus. The stimulus consisted of a point-light human walker in profile orientation going either backwards or forwards. The point-light walker was designed using motion capture data from a real walker and a 3D animation technique (Dekeyser et al., 2002; Vanrie & Verfaillie, 2004). The animation was created with MATLAB for Windows XP to play 60 still images (for one step cycle, consisting of two steps) with a frame refreshing rate of 60 Hz on the screen of a Dell monitor. Each image in the full body version consisted of 13 white dots positioned on the major joints of the walker (the head, two shoulders, two elbows, two wrists, two hips, two knees, and two ankles; radius = 3 pixels) on a gray background. The walker subtended 4 cm at a viewing distance of 45 cm. Upper body and lower body walkers were generated drawing only the dots corresponding to the upper (head, two shoulders, two elbows, and two wrists) and lower (two hips, two knees, and two ankles) joints of the body, respectively. For the upper and lower body only stimuli, the dots corresponding to the lower and upper body, respectively, were invisible. To generate the animation of backward motion, the sequence of frames was reversed.

Procedure and design. The experiment was run in a dimly lit and sound-attenuated lab room. On each trial, participants were presented with a sagittal 0° view of the upper, lower, or full body of a point-light walker, facing to the left. They were instructed to press one button when they perceived the figure as walking forward and another button when they perceived the walker as walking backward. Stimuli were presented for 4.5 sec. After stimulus presentation, a response screen appeared asking whether the stimulus figure was moving forward or backward. Two blocks of trials were administered to each participant. Each block contained 20 trials in each of the 6 conditions (2 directions of motion x 3 types of walkers). Stimuli were presented in a random order. Before the beginning of experiment, the set of all stimuli was shown (named as forward or backward walking) and written instructions were given. Feedback was provided after each trial and after each block of trials (by giving the percentage of correct responses).

RESULTS AND DISCUSSION

A signal detection analysis was performed (classifying forward motion as the "signal" and backward motion as the "noise"). Sensitivity (d') values are depicted in Figure 3. In a repeated measures one-way analysis of variance (ANOVA) with visible body part (upper, lower, full) as within-subject variable, Mauchly's tests indicated that the assumption of sphericity for that variable had been violated ($\chi^2(2) = 10.912$, $p = .004$). Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = .606$). The ANOVA yielded a significant main effect of body part, $F(1.212, 15.758) = 470.541$, $p < .001$. Planned comparisons showed that d' for the upper part condition ($M = -.079$, $SE = .114$) was lower than d' for the lower part ($M = 4.078$, $SE = .160$), $p < .001$ and the full body conditions ($M = 4.402$, $SE = .046$), $p < .001$. As expected, when only the (less informative) upper body part was visible, discrimination between forward and backward motion was impossible. When the (more informative) lower part was visible, discrimination was equivalent to performance with the full body. It is obvious that, for the walking action, direction discrimination based on the analysis of relative motion is primarily driven by the motion of the lower limbs.

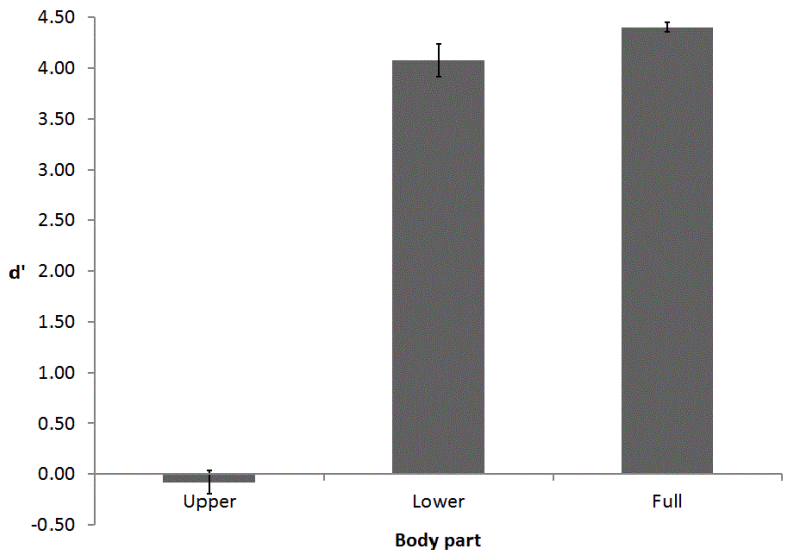

Figure 3. **d' (including standard error bars) as a function of visible body part in Experiment 1.**

Figure 4 depicts the c values. Mauchly's test indicated that the assumption of sphericity for the body part had not been violated ($\chi^2(2) = 1.776$, $p = .411$). The ANOVA did not yield a significant main effect of body part, $F(2, 26) = .641$, $p = .535$.

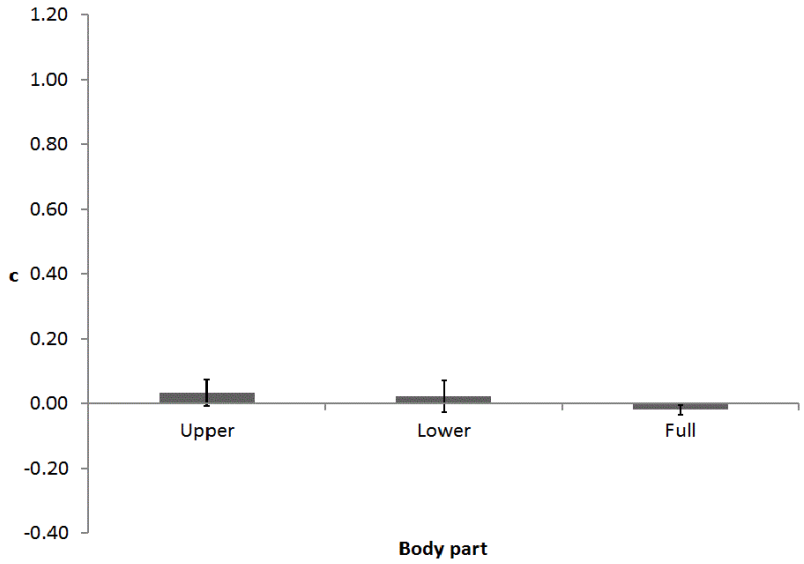

Figure 4. **c (including standard error bars) as a function of visible body part in Experiment 1.**

EXPERIMENT 2

In Experiment 2, we again manipulated the available body part information (full, upper, or lower) of a point-light walker. In addition, under the assumption that the diagnosticity of the information signalling walking direction varies with the viewpoint from which the walker is observed, the in-depth orientation of the point-light walker was varied.

We predicted, as in Experiment 1, that performance would be worst when only the upper part of the body was visible and that performance in the condition in which only the lower part was visible would not differ much from the full-body condition. The new prediction in Experiment 2 was that performance would deteriorate in frontal orientation conditions in comparison to the other orientation conditions.

METHOD

Participants. 14 students of psychology at the KU Leuven with normal vision or corrected to normal vision (12 women, 2 men, $M_{age} = 18.57$, $SD_{age} = .542$ years) participated in this experiment. None of them had taken part in the previous experiment.

Stimuli. The point-light human walker as used in Experiment 1 was now shown in one of four possible orientations: the 0° profile orientation, the 90° frontal orientation or the 30° or 60° orientation in between. Again, the walker was going either forwards or backwards as moving on a treadmill and the full body, only the upper body, or only the lower body was shown.

Procedure and design. As in Experiment 1, participants on each trial had to indicate whether the walker was moving forward or backward. Two blocks of trials were administered to each participant. Each block contained 120 trials consisting of 5 trials for each of the 24 conditions (2 directions of motion x 3 types of walkers x 4 orientations). The sequence of trials within each block was again randomized.

RESULTS AND DISCUSSION

In a repeated measures ANOVA on d' (see Figure 5) with visible body part (upper, lower, full) and depth orientation (0°, 30°, 60°, and 90°) as within-subject variables, Mauchly's tests indicated that the assumptions of sphericity for the effect of body part ($\chi^2(2) = 11.261$, $p = .004$), orientation ($\chi^2(5) = 17.357$, $p = .004$), and the interaction between body part and orientation ($\chi^2(20) = 84.215$, $p < .001$) were violated. Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity for the body part ($\varepsilon = .622$), orientation ($\varepsilon = .555$), and the interaction ($\varepsilon = .439$). The ANOVA yielded a significant main effect of body part, $F(1.243, 16.162) = 237.005$, $p < .001$, and orientation, $F(1.665, 21.650) = 6.472$, $p = .009$. The interaction between body part and orientation, $F(2.635, 34.253) = 2.156$, $p = .118$ was not significant. Planned comparisons showed that d' for the upper part conditions ($M = .277$, $SE = .159$) was lower than d' for the lower part ($M = 2.972$, $SE = .085$, $p < .001$) and full body conditions ($M = 3.196$, $SE = .022$, $p < .001$) and that d' for the frontal orientation ($M = 1.773$, $SE = .144$) was lower than d' for the profile ($M = 2.246$, $SE = .106$, $p = .014$), 30° ($M = 2.339$, $SE = .094$, $p = .006$), and 60° orientation ($M = 2.237$, $SE = .060$, $p = .001$), as predicted.

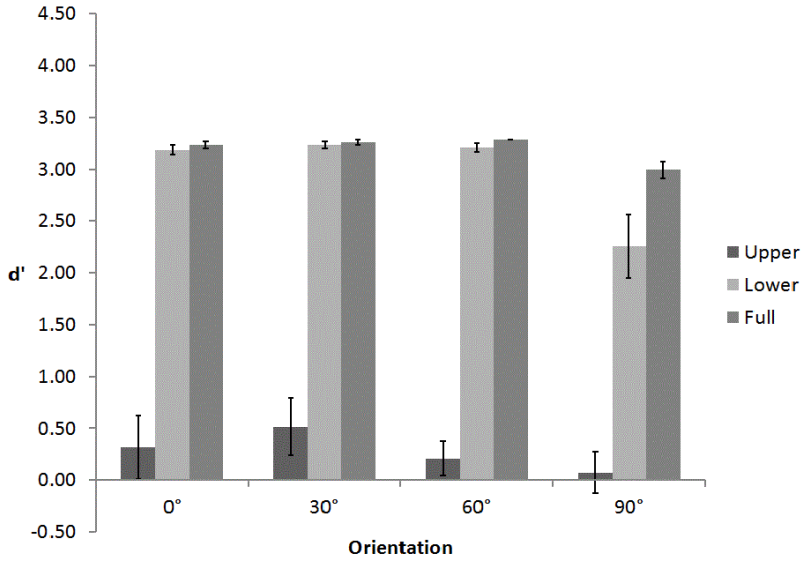

Figure 5. **d' (including standard error bars) as a function of visible body part and figure orientation in Experiment 2.**

In an ANOVA on c, (Figure 6) Mauchly's tests indicated that the assumptions of sphericity for body part ($\chi^2(2) = 6.941$, $p = .031$), orientation ($\chi^2(5) = 12.352$, $p = .031$), and the interaction between body part and orientation ($\chi^2(20) = 83.587$, $p < .001$) were violated. Degrees of freedom were corrected using Huynh-Feldt estimate of sphericity for body part ($\varepsilon = .752$), and Greehouse-Geisser estimates for orientation ($\varepsilon = .597$) and the interaction ($\varepsilon = .349$). (One note is in order here. Sphericity within this context means equality between any pair of variances of differences. For instance, we have three body parts conditions and three possible pairs of variances of differences: variance of the difference between upper and lower vs. variance of the difference between upper and full, variance of the difference between upper and lower vs. variance of the difference between lower and full, variance of the difference between lower and full vs. variance of the difference between upper and full. There at least two possible corrections for violations of sphericity: The Greenhouse-Geisser estimate e^ and the Huynh-Feldt estimate (e~). e^ is too conservative causing incorrect acceptance of the null hypothesis that sphericity does hold, when it does not (Type II error). e~ is too liberal causing incorrect rejection of the null hypothesis that sphericity does hold, when it does (Type I error). Girden (1992; also, see Barcikowski & Robey, 1984) recommends that when e^ > 0.75 then the df should be corrected using e~. If e^ < 0.75, or nothing is known about sphericity at all, then the conservative e^ should be used to adjust the df.)

The ANOVA yielded a significant main effect of body part, $F(1.503, 19.544) = 38.659$, $p < .001$. The main effect of orientation, $F(1.790, 23.275) = 1.452$, $p = .254$ and the interaction effect between body part and orientation, $F(2.092, 27.192) = .597$, $p = .565$ were not significant. Post-hoc comparisons showed that c values for the upper part conditions ($M = .360$, $SE = .049$) were higher than for the lower part ($M = .018$, $SE = .026$, $p < .001$), and full body conditions ($M = -.021$, $SE = .013$, $p < .001$). However, this was not observed in Experiment 1 (and neither in subsequent experiments). The reason for this discrepancy is unclear at present.

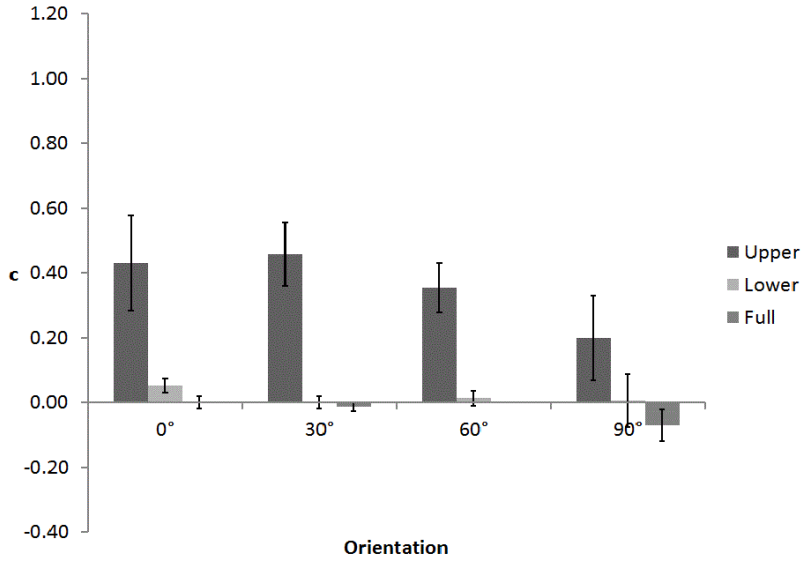

Figure 6. **c (including standard error bars) as a function of visible body part and figure orientation in Experiment 2.**

EXPERIMENT 3

In Experiments 1 and 2, we observed that the perception of motion direction of a walker on the basis of the articulatory, relative motions of the limbs is mainly driven by the motion of the lower limbs. This indirectly supports the hypothesis of a life detector mechanism particularly sensitive to the movements of the legs. However, for other, less common, types of human locomotion the movements of the arms might become more informative. In Experiment 3, participants were presented with a crawling action instead of a walking action, again either showing the full body or only the upper or lower body. We expected that in this case not only the lower body but also the upper body would be diagnostic for the direction of articulation. In addition, the depth orientation of the actor was

manipulated as in Experiment 2, again under the assumption that, as the orientation was further away from the most informative sagittal view, performance would deteriorate.

METHOD

Participants. 14 students of psychology at the KU Leuven (12 women, 2 men, M_{age} = 18.95, SD_{age} = 1.18 years) participated in this experiment. They did not take part in the previous experiments, had normal or corrected-to-normal vision, and were naïve to the purpose of the study.

Stimuli. Participants were presented with the crawling action of the action database of Vanrie and Verfaillie (2004). On each trial, the action was again presented in one of four possible depth orientations: 0° (sagittal), 30°, 60°, or 90° (frontal). Either the full crawler or only the upper or lower body part was shown.

Procedure and design. The procedure was the same as in Experiment 2. Participants had to indicate the perceived direction of articulatory movement of upper, lower, or full crawlers shown in different depth orientations. Two blocks of trials, each containing 120 trials (5 repetitions of 24 unique trials resulting from the manipulation of 2 directions of motion, 3 types of crawlers, and 4 orientations) were administered to each participant.

RESULTS AND DISCUSSION

A repeated measures ANOVA was performed on d' (see Figure 7) with visible body part (upper, lower, or full) and depth orientation (0°, 30°, 60°, or 90°) as within-subjects variables. Because Mauchly's tests indicated that the assumptions of sphericity for body part ($\chi^2(2) = 8.842$, $p = .012$), orientation ($\chi^2(5) = 42.807$, $p < .001$), and the interaction between body part and orientation ($\chi^2(20) = 90.214$, $p < .001$) were violated, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity for body part ($\varepsilon = .657$), orientation ($\varepsilon = .397$), and the interaction ($\varepsilon = .323$). The ANOVA yielded a significant main effect of orientation, $F(1.192, 15.501) = 84.019$, $p < .001$. Planned comparisons showed that d' for the frontal orientation (M = .742, SE = .257) was lower than for the profile (M = 3.253, SE = .021, $p < .001$), 30° (M = 3.197, SE = .058, $p < .001$), and 60° orientation (M = 3.111, SE =.068, $p < .001$). As predicted, the frontal view is less informative for determining the motion direction of the crawler. The main effect of body part, $F(1.315, 17.090) = .520$, $p = .529$, and the interaction between body part and orientation, $F(1.936, 25.170) = .401$, $p = .667$, were not significant. This suggests that, in contrast to walking, for crawling both the

upper and the lower body part are diagnostic for determining the direction of articulatory motion.

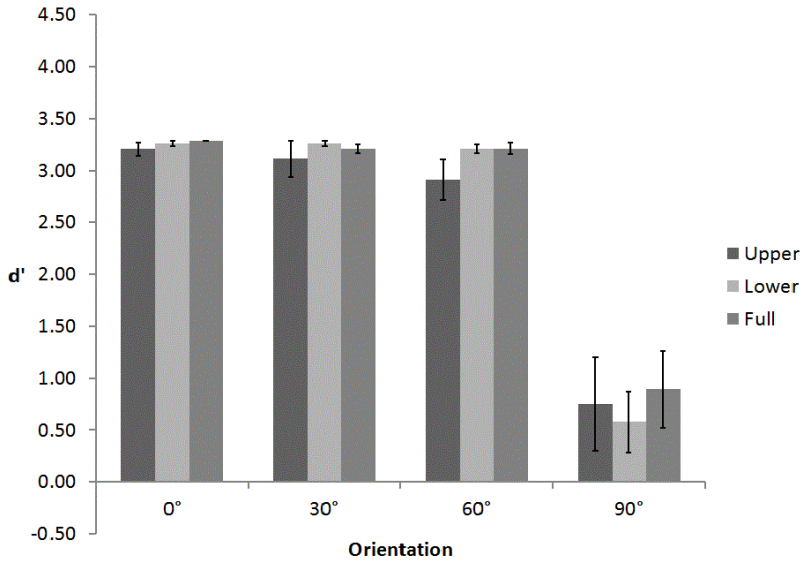

Figure 7. **d' (including standard error bars) as a function of visible body part and figure orientation for the crawling action in Experiment 3.**

In an ANOVA on c, (Figure 8) Mauchly's tests indicated that the assumptions of sphericity for orientation ($\chi^2(5) = 34.005$, $p < .001$) and the interaction between body part and orientation ($\chi^2(20) = 98.790$, $p < .001$) were violated. Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity for orientation ($\varepsilon = .406$) and the interaction ($\varepsilon = .377$). The main effects of body part, $F(2, 26) = .762$, $p = .477$, and orientation, $F(1.218, 15.835) = 1.964$, $p = .180$, and the interaction between body part and orientation, $F(2.262, 29.401) = .254$, $p = .803$ were not significant.

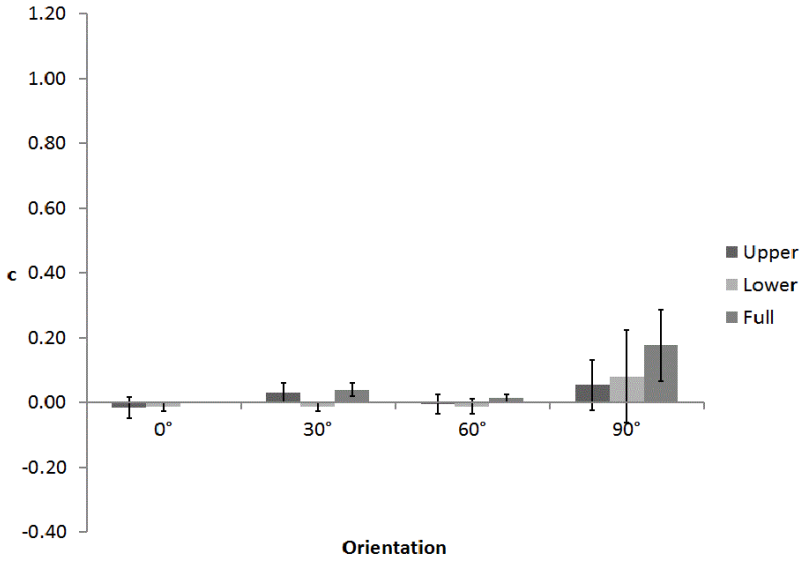

Figure 8. **c (including standard error bars) as a function of visible body part and figure orientation in Experiment 3.**

EXPERIMENT 4

In Experiment 4, we presented participants with a (very uncommon) action for which the direction of articulatory motion probably is mainly perceived on the basis of the movements of the arms and the legs carry no useful information at all, namely hand walking. Participants again had to indicate the direction of articulatory motion and viewpoint and visible body part were manipulated as in the previous experiments. (Note that, because the actor is inverted, reference to upper and lower body parts becomes ambiguous now; we refer to the arms when we mention the upper body part and to the legs when we mention the lower body parts.)

METHOD

Participants. 13 female and 1 male new students of psychology at the KU Leuven (M_{age} = 18.59, SD_{age} = 0.41 years) and naïve with respect to the purpose of the study participated in this experiment.

Stimuli. A point-light human hand walker was created using Autodesk 3ds Max 2012 (2011) and a .csm file produced by Red Eye Studio (2002). The size of the stimulus was adapted to make it equivalent to the standard sizes of the stimuli from the Leuven Action Database used in the previous experiments.

Procedure and design. We used the same procedure and design as in Experiments 2 and 3.

RESULTS AND DISCUSSION

In a repeated measures ANOVA on d' (see Figure 9) Mauchly's tests indicated that the assumptions of sphericity for body part ($\chi^2(2) = 16.402$, $p = < .001$) and orientation ($\chi^2(5) = 19.592$, $p = .002$) had been violated. Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity for body part ($\varepsilon = .573$) and orientation ($\varepsilon = .494$). The ANOVA yielded a significant main effect of body part, $F(1.146, 14.899) = 164.069$, $p < .001$, and orientation, $F(1.481, 19.247) = 19.377$, $p < .001$, and a significant interaction effect between body part and orientation, $F(6, 78) = 8.762$, $p < .001$. Planned comparisons showed that d' for the lower body part ($M = .474$, $SE = .159$) was lower than d' for the upper body part ($M = 2.512$, $SE = .092$) and full body ($M = 2.580$, $SE = .078$, $p < .001$). As in the previous experiments, d' for the frontal orientation ($M = .833$, $SE = .244$) was lower than for the profile ($M = 2.231$, $SE = .146$, $p = .001$), 30° ($M = 2.264$, $SE = .117$, $p < .001$), and 60° orientation ($M = 2.095$, $SE = .088$, $p < .001$).

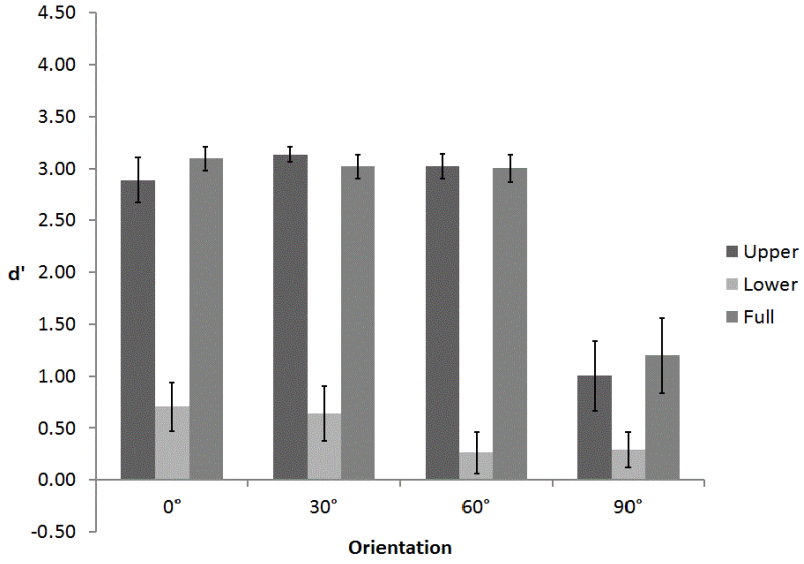

Figure 9. **d' (including standard error bars) as a function of visible body part and figure orientation in Experiment 4.**

In an ANOVA on c (Figure 10), Mauchly's tests indicated that the assumptions of sphericity for body part ($\chi^2(2) = 12.865$, $p = .002$) and the interaction between body part and orientation ($\chi^2(20) = 35.655$, $p = .021$) had been violated. Therefore, degrees of freedom

were corrected using Greenhouse-Geisser estimates of sphericity for body part (ε = .631) and Huynh-Feldt estimates of sphericity for the interaction (ε = .793). The main effects of body part, F(1.206, 15.684) = .638, p = .808, and orientation, F(3, 39) = .862, p = .187, and the interaction between body part and orientation, F(4.756, 61.825) = 1.447, p = .471, were not significant.

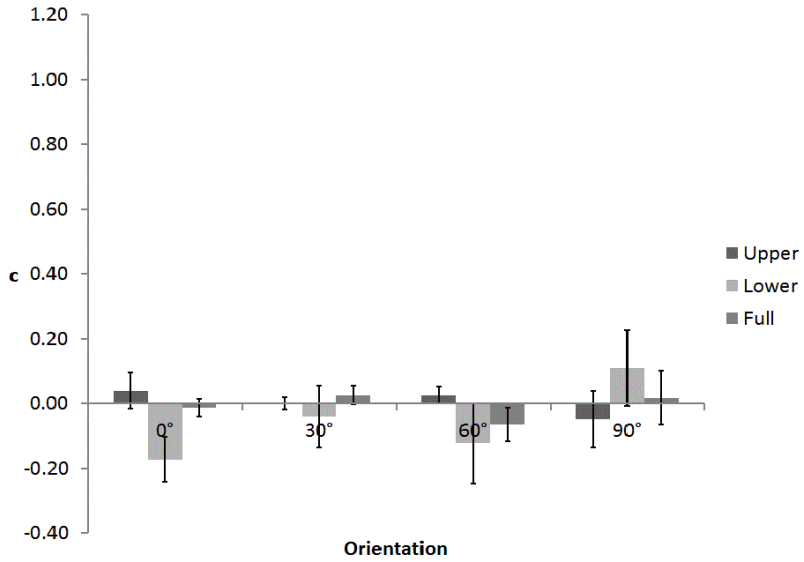

Figure 10. **c (including standard error bars) as a function of visible body part and figure orientation in Experiment 4.**

EXPERIMENT 5

The purpose of the final experiment was to study perception of motion direction in a rowing action, an action in which (in contrast to walking and crawling) the upper limbs probably are more diagnostic than the lower limbs. Participants again had to indicate the direction of articulatory motion and the figure's depth orientation and the visible body part was manipulated.

Rowing diverges from the actions presented in the previous four experiments in several respects. First, forward direction of motion is opposite to the facing direction of the mover. Second, like in hand walking, motion direction probably is best signalled by the movements of the upper limbs (and not by the lower limbs), but in contrast to hand walking the limbs produce a lot of (albeit non-diagnostic) motion energy. Third, and maybe most importantly, unlike walking, rowing, and hand walking (intransitive motion), direct contact of the limbs with the ground surface is not the source of translatory motion of the body as a

whole. Rather, forward motion originates from moving (in this case) rotating an external device (in this case peddles) indirectly acting on the external environment (transitive motion). (Another typical example of a transitive action including rotatory motion of a tool is cycling.)

METHOD

Participants. 14 new students of psychology at the KU Leuven (11 women, 3 men, M_{age} = 18.93, SD_{age} = 1.01 years) participated.

Stimuli. We selected the rowing action from the point-light action database from Vanrie and Verfaillie (2004). The action displays a man rowing in a stationary standard boat (i.e., the translational motion component was removed). The action was again presented in one of four possible depth orientations: 0° (sagittal), 30°, 60°, or 90° (frontal) and either the full rower or only the upper or lower body part was shown.

Procedure. The procedure was the same as in Experiments 2, 3, and 4. Each participant was administered two blocks of 120 trials (each block containing 5 trials in each of 24 conditions (2 directions of motion x 3 types of rowers x 4 orientations)).

RESULTS AND DISCUSSION

Sensitivity values (d') as a function of visible body part and depth orientation are shown in Figure 11. In a repeated measures ANOVA, Mauchly's tests indicated that the assumptions of sphericity for body part ($\chi^2(2) = 7.514$, $p < .023$) and the interaction between body part and orientation ($\chi^2(20) = 48.920$, $p < .001$) had been violated. Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity for body part ($\varepsilon = .682$) and the interaction ($\varepsilon = .529$). The main effect of body part, $F(1.365, 17.743) = 276.573$, $p < .001$, and of orientation, $F(3, 39) = 10.082$, $p < .001$, were statistically significant. The interaction between body part and orientation, $F(3.174, 41.256) = 1.172$, $p = .333$, was not significant. Planned comparisons showed that d' for the lower body part (M = .119, SE = .136) was lower than d' for the upper body part (M = 2.759, SE = .114) and d' for the full body (M = 2.741, SE = .149, $p < .001$). When the rower was seen in a frontal orientation d' (M = 1.455, SE = .158) was lower than when seen in a profile orientation (M = 1.903, SE = .166, $p = .008$), 30° orientation (M = 2.073, SE = .099, $p = .001$), or 60° orientation (M = 2.061, SE =.110, $p < .001$). This confirms the prediction that, for a rowing action, the direction of articulatory motion is mainly driven by the motion of the upper limbs and that the frontal view is less diagnostic than the other views.

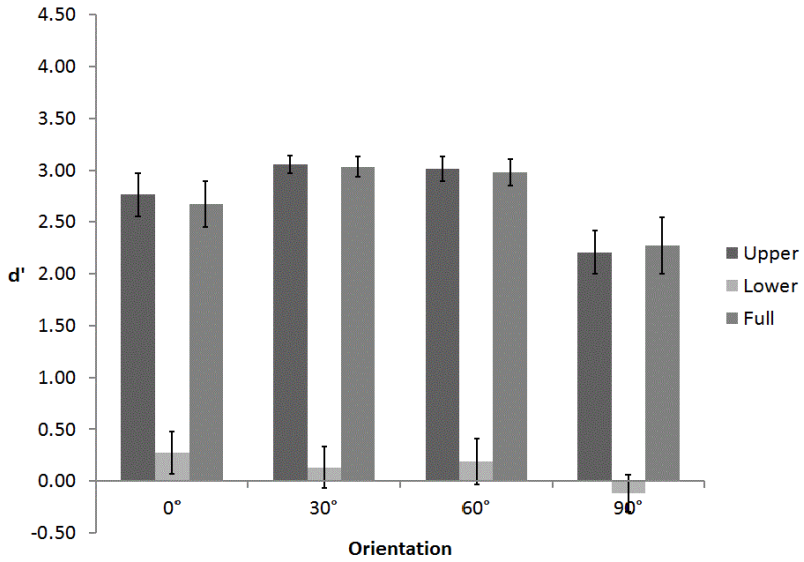

Figure 11. **d' (including standard error bars) as a function of visible body part and figure orientation in Experiment 5.**

In an ANOVA on c, (Figure 12) Mauchly's tests indicated that the assumptions of sphericity for the interaction between body part and orientation ($\chi^2(20) = 35.349$, $p = .022$) had been violated. Therefore, degrees of freedom for the interaction were corrected ($\varepsilon = .787$). The ANOVA yielded a significant main effect of orientation, $F(3, 39) = 4.377$, $p = .015$. Apparently, when confronted with the less informative frontal orientation, participants showed a tendency to interpret the low-informative stimulus as moving forward rather than backward. The main effect of body part, $F(2, 26) = .624$, $p = .544$, and the interaction between body part and orientation, $F(4.721, 61.368) = 1.131$, $p = .353$ were not significant.

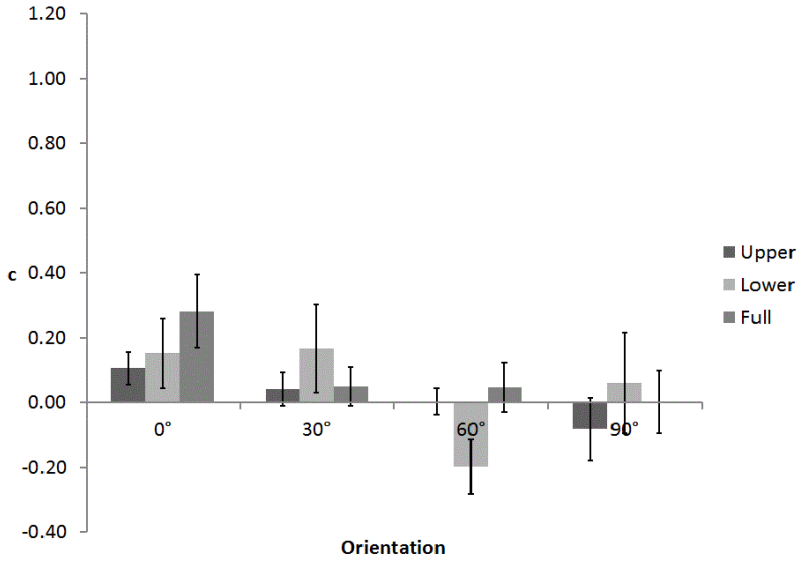

Figure 12. **c (including standard error bars) as a function of visible body part and figure orientation in Experiment 5.**

GENERAL DISCUSSION

The main purpose of the present study was to examine the perception of motion direction of point-light actions on the basis of the articulatory relative motions of the limbs. Most importantly, this question was addressed not only for the action of walking (as done in previous studies), but also for the actions of crawling, hand walking, and rowing. In addition, we manipulated the diagnosticity of the information available for detection the direction of articulatory motion by varying the visible body part (upper, lower, vs. full body) and the viewpoint from which the action was seen.

We observed that sensitivity for the direction of articulatory motion varies with the action: For walking the lower limbs are most diagnostic, for crawling both the upper and the lower limbs, for hand walking the upper limbs, and for rowing the upper limbs. The main conclusion is that, not surprisingly, the limbs thak make contact to the ground surface and therefore enable locomotion are critical for the perception of direction of articulation.

In addition, performance in general was worst for the least informative frontal orientation (Kuhlmann et al., 2009). This makes sense given that, for the actions used in the present study, the limbs almost entirely move in the midsagittal plane, i.e., in planes symmetrical to the facing direction of the moving figure (Hoffman & Flinchbaugh, 1982; Webb & Aggarwal, 1982). Information on motion direction in these planes obviously is weaker as the figure approaches the frontal/back view.

The next logical step in this research project is to try to relate sensitivity to quantitative stimulus characteristics for different actions in different depth orientations. We assume that for the task of classifying the horizontal direction of articulation of point-light figures, the asymmetry in the direction of motion of the dots is the critical information that produces performance. More specifically, we hypothesize that the relevant kinematic properties associated to this asymmetry are asymmetries between horizontal forward and backward motion in duration, velocity, and/or acceleration of individual or groups of dots. For instance, in the case of the action of walking, the upper body part in frontal orientation might be poorly informative because of the lack of asymmetry between forward and backward motion characteristics. A way to measure this (a)symmetry is calculating the absolute value of the difference between the duration, velocity, or acceleration when moving forwards and their correspondents when moving backwards and averaging these measures over dots. In Table 1 we present the Pearson correlation between sensitivity on the one hand and the asymmetry between forward and backward motion for duration, velocity, and acceleration for the upper and lower body in the different actions (averaged across orientations) on the other hand. As expected, for walkers performance is driven mostly by perception of the lower limbs, for crawlers by both upper and lower limbs, for hand walkers by upper limbs, and for rowers by upper limbs as well. We report a detailed study of the relation between sensitivity and stimulus in Chapter 4.

Table 1

Pearson correlation between sensitivity on the one hand and the asymmetry between forward and backward motion for duration, velocity, and acceleration for the upper and lower body in the different actions on the other hand.

	Walker		Crawler		Hand walker		Rower	
	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower
Duration	0.175	0.434	0.387	0.773***	0.702***	0.109	0.582***	-0.138
Velocity	-0.156	0.472	-0.376	-0.719***	-0.600**	-0.304*	-0.301*	0.228
Acceleration	0.199	0.553***	0.507***	0.730***	0.673***	-0.050	0.531***	-0.118

*p<.05. **p<.01. ***p<.001.

Note that, despite the long stimulus duration relative to other studies, d' was still low for the upper body (for walking) or lower body (for hand walking). The long duration could have hidden differences between upper and lower limbs in the crawling condition, as d' was

very high in all but the 90 degree orientation condition. Future studies should examine the effects of stimulus duration on the use of different body parts in biological motion perception, especially given our interest in the possibility of an innate visual filter that is tuned to quickly and automatically detect actions.

As mentioned in the Introduction of this Chapter, Troje and colleagues suggested that a specialized life detector is activated during the perception of animate locomotion. Obviously, the present data do not provide *direct* empirical evidence for the existence of a life detector mechanism. On the other hand, our findings are not in disagreement with such an account. Moreover, and this is speculative, if such a mechanism indeed underlies the behavior of the participants in the present experiments, the observations suggest an extension of the idea of a life detector as originally conceived of. Indeed, it is not the case that the lower limbs necessarily and exclusively carry the most useful information. Instead, for other actions (like crawling) both the upper and lower limbs are diagnostic for motion direction or (like hand walking) the lower limbs are not informative at all and information on the upper limbs drive the decision on the direction of motion. Apparently, and almost trivially, the most important factor is which limbs are directly responsible for direct contact with – and therefore locomotion – across the ground surface: the feet in the case of walking, the hands in the case of hand walking, and the hands and the feet in the case of crawling. Whether there is also something "special" about animate motions in the case of transitive actions (in which locomotion results from physical action on a tool) is an open question.

Chapter 4

Phase portrait analysis of actions

ABSTRACT

The goal of this chapter is the introduction of a novel technique based on phase portrait procedures to explain sensitivity responses in psychophysical experiments as those we reported in Chapter 3. The chapter follows this sequence: First, we summarize the main findings of our research reported in Chapter 3 and explain the need for a technique to measure the amount of asymmetry in the horizontal direction of motion of animated actions. Second, we use the direction of the velocity of a single dot to deduce four indices to measure symmetry/asymmetry of the direction of its motion and the phase portrait representation. Later, we use these indices and the phase portrait representation to compare the motion of an ideal simple physical pendulum (ideal example of symmetry in the direction of motion) and the motion of the ankle in human walking (real example of asymmetry in the direction of motion). Third, we apply the technique to the analysis of asymmetry of motion of individual joints clustered by body parts and varying for orientations from profile to frontal view, for the actions of walking, crawling, hand walking, and rowing. Fourth, we apply the technique to the analysis of asymmetry of motion of body parts using averaged kinematic information from joints. Finally, we discuss the benefits and limitations that applying the technique might have for the understanding of human perception of biological motion or motion explained by physical variables.

INTRODUCTION

As already spelled out in Chapter 3, the horizontal movement direction of an animated point-light action articulating without the global translatory component of motion (common motion), may be signaled by different sources of information. We reported in that chapter four experiments (each one for a particular action) for which two sources of information from the animated action were manipulated. Varying the viewpoint (going from the profile to the frontal orientation) from which the point-light stimulus is seen and the visible part of the body (upper, lower, or full); participants had to decide on the direction of articulation of the point-light animation.

To summarize our previous results for performance: First, when classifying the direction of articulation, performance lowers when observers view a relatively less informative body part of an animation (the upper or lower part of the body depending on the specific action). Second, frontal orientations are relatively less informative to classify correctly the direction of articulation of animated figures.

Point-light animated actions are complex stimuli. The action of walking has probably been studied the most. For this action, on one hand, local motion processes have been reported to indicate the facing direction (Hirai, Chang, Saunders, & Troje, 2011), and the local inversion effect (Chang & Troje, 2008). On the other hand, global motion perception processing has also been shown to be important in biological motion perception (Bertenthal & Pinto, 1994).

We assume that for the task of classifying the horizontal direction of articulation of point-light figures, the asymmetry in the direction of motion of the dots is the critical information that produces the performance as observed in Chapter 3. We hypothesize that the relevant kinematic properties associated to this asymmetry are asymmetries between horizontal forward and backward motion in duration, velocity, and/or acceleration of individual or groups of dots.

For instance, in the case of the action of walking, the upper body part in frontal orientation might be poorly informative because of the lack of asymmetry between forward and backward duration, horizontal velocity, and/or horizontal acceleration of the dots that compose it.

Kinematic properties of angular position and velocity have been analyzed simultaneously using phase portrait figures to understand the ontogeny of human gait and its variability (Polk et al., 2008) or its complexity and variability (DiBerardino III, Polk, Rosengren, Spencer-Smith, & Hsiao-Wecksler, 2010). In mathematics and physics, a phase portrait is a graphical depiction of the trajectories of a dynamical system. A dynamical system is "a set of possible states, together with a rule that determines the present state in terms of past states" (Alligood, Sauer, & Yorke, 1997, p. 285). For instance, in the case of the analysis of horizontal motion involved in the animation of human actions, quantitative analysis should be possible using horizontal position and change of horizontal position and represented together as a phase portrait.

To our current knowledge, phase portrait techniques or related kinematic analysis have not been applied yet to the analysis of asymmetry of the direction of motion of dots that compose point-light figures. We consider that the application of these techniques may be

useful to represent and then analyze the kinematic complexity of animations depicting human actions.

ANALYSIS OF PHYSICAL ASYMMETRIES OF THE DIRECTION OF HORIZONTAL MOTION OF POINT-LIGHT ANIMATIONS

The direction of horizontal motion we plan to study, corresponds to the horizontal direction (forwards or backwards) of the curvilinear and periodical motion of any individual dot composing a particular animation moving either forwards or backwards. In the case of animations of human actions without the global translatory component of motion (common motion), this periodical motion describes a closed path that starts and ends at the same point for each repetition of the periodic movement.

Figure 13 illustrates the trajectories of periodical motions on a XZ plane correspondent to the head and the joints located on the left side of a human body shown in profile orientation and facing to the left while walking as if on a treadmill. As a convention we will further assume that moving from the right to the left will be moving forwards; and from the left to the right, moving backwards.

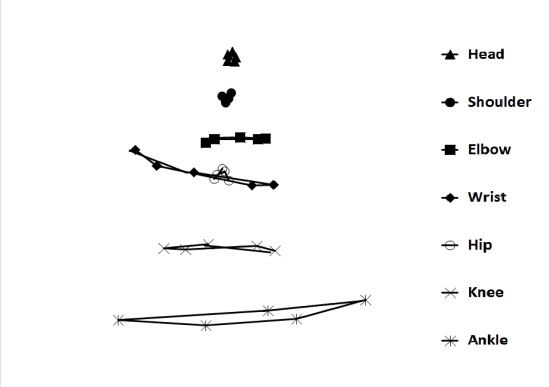

Figure 13. **Trajectories on a XZ plane of seven dots correspondent to the head, left shoulder, left elbow, left wrist, left hip, left knee, and left ankle of a human walker shown in profile orientation while walking stationary (as if on a treadmill). For illustrative purposes only five positions for each dot are depicted.**

To illustrate and explain the measures of asymmetry, we will compare the kinematic properties of the motion of an ideal simple physical pendulum (ideal example of symmetry in the direction of motion) and the motion of the ankle in human walking (real example of asymmetry in the direction of motion).

To achieve our purpose, we need a procedure to distinguish between horizontal forward and backward motion (as defined above) using phase portrait techniques and a procedure to study kinematic properties of the dots that compose animations. The procedure that solves both needs is computing the first and second derivatives of the horizontal position using the central difference numerical differentiation method (Robertson & Caldwell, 2004).

Using this method, on one hand we may express the definition of forward motion as defined above in a mathematical way stating that $x_{n+1} < x_{n-1}$; where x_{n-1} is the initial horizontal position of an individual dot in frame n-1 and x_{n+1} is the final horizontal position in frame n+1. On the other hand, velocity of an individual dot correspondent to a specific frame n may be defined as $v_n = (x_{n+1} - x_{n-1})/2$ and acceleration as $a_n = (v_{n+1} - v_{n-1})/2$. Note that with the present definitions of forward motion and velocity, forward motion is equivalent to negative velocity and backward motion to positive velocity.

TEMPORAL INDEX OF ASYMMETRY (TIA)

Figure 14 on the left depicts an example of symmetry between the duration of forward and backward motion correspondent to the animation of an ideal periodic motion (30 frames). Using the rules described above, we found 14 dots representing horizontal positions when moving forwards (below the horizontal axis) and 14 dots representing horizontal positions when moving backwards (above the horizontal axis).

As each occupied position corresponds to a single frame of an animation and each frame has a fixed duration, the ideal periodic motion should spend the same amount of time moving forwards and backwards until completing a full cycle of motion. A way to measure this symmetry is calculating the absolute value |amount of time moving forwards - amount of time moving backwards| = |number of dots moving forwards - number of dots moving backwards|*duration of each dot depiction = |15-15|*duration of each dot depiction = 0. This represents perfect symmetry between the durations of forward and backward motions irrespective of any constant time spent by dots on the screen for a particular frame rate.

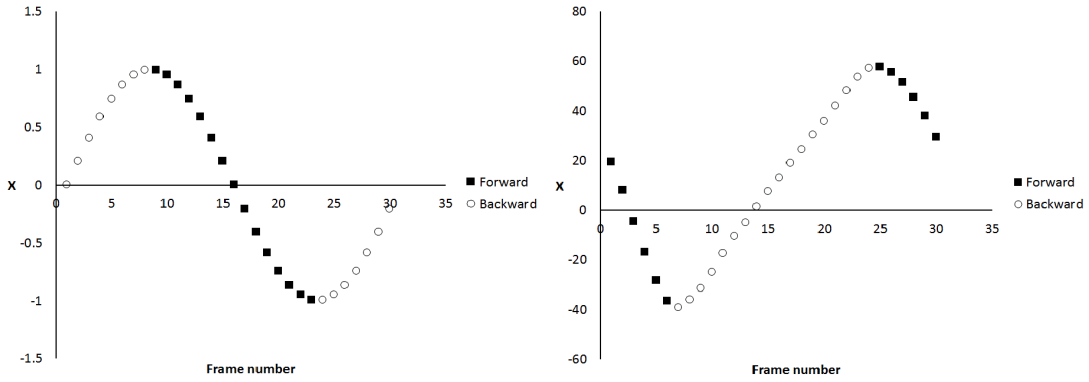

Figure 14. **Left. Horizontal positions X of a dot correspondent to an ideal periodic motion. Right. Horizontal positions X of a dot correspondent to the motion of a left ankle in human walking as if on a treadmill. For both systems the number of frames correspondent to the total number of occupied horizontal positions is 30.**

Figure 14 on the right depicts an example of asymmetry between the duration of animated forward and backward motion correspondent to the motion of the left ankle in human walking as if on the treadmill. For this case, we found 12 horizontal positions when moving forwards and 18 horizontal positions when moving backwards. The correspondent absolute value difference |amount of time moving backwards - amount of time moving forwards| = |18-12|* duration of each dot depiction = 6*duration of each dot depiction.

We will call the above calculated values for the pendulum and the human ankle Temporal Index of Asymmetry (TIA). This value represents asymmetry between the durations of forward and backward motions if it differs from zero. Suppose that this animation is displayed using a frame rate of 30 Hz, then each frame would last approximately 33.33 ms. As the animation is composed of 12 frames moving forwards and 18 frames moving backwards; the amount of time spent to move forwards would be approximately 400 ms, to move backwards approximately 600 ms, and the difference between these durations approximately 200 ms. If the animation is displayed using a frame rate of 60 Hz then each frame would last approximately 16.67 ms and the amount of time to move forwards about 200 ms, to move backwards about 300 ms, and the difference between them about 100 ms.

Table 2 depicts the detailed calculations of the TIA for the cases of the pendulum and the human ankle considering normalized units for duration. Duration of each frame exposure is taken as one.

For animations composed of 30 frames, TIA possible values are between 0 and 29 multiplied by the duration of each frame exposure.

Table 2

Analysis of the symmetry/asymmetry between forward and backward horizontal motion of an ideal periodic motion and of the left ankle in human walking as if on the treadmill. X: horizontal position; dX/dt: horizontal velocity; Sign: sign of horizontal velocity; FT: forward time frame; BT: backward time frame.

Ideal periodic motion					Left ankle in human walking				
X	dX/dt	Sign	FT	BT	X	dX/dt	Sign	FT	BT
0.00	0.21	1		1	19.5	-10.75	-1	1	
0.21	0.20	1		1	8.0	-12.00	-1	1	
0.41	0.19	1		1	-4.5	-12.50	-1	1	
0.59	0.17	1		1	-17.0	-12.00	-1	1	
0.74	0.14	1		1	-28.5	-9.75	-1	1	
0.87	0.10	1		1	-36.5	-5.25	-1	1	
0.95	0.06	1		1	-39.0	0.25	1		1
0.99	0.02	1		1	-36.0	3.75	1		1
0.99	-0.02	-1	1		-31.5	5.50	1		1
0.95	-0.06	-1	1		-25.0	7.00	1		1
0.87	-0.10	-1	1		-17.5	7.25	1		1
0.74	-0.14	-1	1		-10.5	6.25	1		1
0.59	-0.17	-1	1		-5.0	6.00	1		1
0.41	-0.19	-1	1		1.5	6.25	1		1
0.21	-0.20	-1	1		7.5	5.75	1		1
0.00	-0.21	-1	1		13.0	5.75	1		1
-0.21	-0.20	-1	1		19.0	5.75	1		1
-0.41	-0.19	-1	1		24.5	5.75	1		1
-0.59	-0.17	-1	1		30.5	5.75	1		1
-0.74	-0.14	-1	1		36.0	5.75	1		1
-0.87	-0.10	-1	1		42.0	6.00	1		1
-0.95	-0.06	-1	1		48.0	5.75	1		1
-0.99	-0.02	-1	1	1	53.5	4.50	1		1
-0.99	0.02	1		1	57.0	2.00	1		1
-0.95	0.06	1		1	57.5	-0.75	-1	1	
-0.87	0.10	1		1	55.5	-3.00	-1	1	
-0.74	0.14	1		1	51.5	-5.00	-1	1	
-0.59	0.17	1		1	45.5	-6.75	-1	1	
-0.41	0.19	1		1	38.0	-8.00	-1	1	
-0.21	0.20	1		1	29.5	-9.25	-1	1	
		Frames	15	15			Frames	12	18
		Duration	1	1			Duration	1	1
			TIA	0.00				TIA	6.00

VELOCITY INDEX OF ASYMMETRY (VIA)

Figure 15 on the left depicts the velocities of forward and backward motion correspondent to the motion of an animated ideal simple physical pendulum. Dots below the horizontal axis correspond to forward motion and above to backward motion. A way to measure the symmetry/asymmetry in velocity for this system is calculating |average velocity moving forwards - average velocity moving backwards|. If these averages do not coincide, it means that there is a difference between the magnitudes of forward and backward average velocities. We will call this difference in absolute value Velocity Index of Asymmetry (VIA).

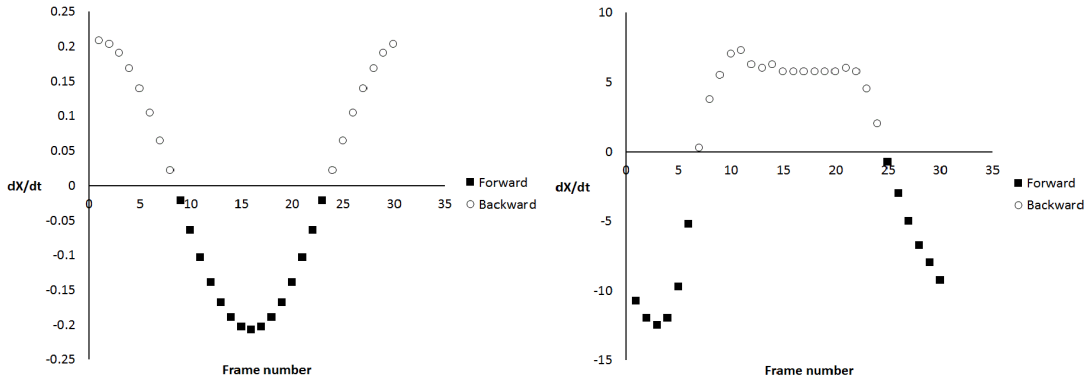

Figure 15. **Left. Horizontal velocities dX/dt of a dot correspondent to the center of mass of an ideal simple physical pendulum oscillating between 20° and -20°. Right. Horizontal velocities dX/dt of a dot correspondent to the motion of a left ankle in human walking as if on a treadmill. For both systems the number of frames correspondent to the total number of depicted horizontal velocities is 30.**

For the pendulum VIA = 0. This means perfect symmetry between the average forward and backward velocities for this system. Figure 15 on the right depicts the velocities of forward and backward motion correspondent to the animated motion of the left ankle in human walking as if on a treadmill. In this case, VIA = 2.64. In general; if VIA = 0, there is perfect symmetry between the forward and backward average velocities; if VIA > 0, there is asymmetry and the system under study on average moves forward and backward with different velocities

Table 3 depicts the detailed calculations of the VIA for the cases of the pendulum and the human ankle. Note that the sum of all velocities in both cases equals zero and the sums of forward and backward velocities coincide.

Table 3

Analysis of the symmetry/asymmetry between forward and backward average horizontal velocities of an ideal simple physical pendulum and of the left ankle in human walking as on the treadmill. X: horizontal position; dX/dt: horizontal velocity; Sign: sign of horizontal velocity; FV: forward velocity; BV: backward velocity.

Ideal periodic motion					Left ankle in human walking				
X	dX/dt	Sign	FV	BV	X	dX/dt	Sign	FV	BV
0.00	0.21	1		0.21	19.5	-10.75	-1	10.75	
0.21	0.20	1		0.20	8.0	-12.00	-1	12.00	
0.41	0.19	1		0.19	-4.5	-12.50	-1	12.50	
0.59	0.17	1		0.17	-17.0	-12.00	-1	12.00	
0.74	0.14	1		0.14	-28.5	-9.75	-1	9.75	
0.87	0.10	1		0.10	-36.5	-5.25	-1	5.25	
0.95	0.06	1		0.06	-39.0	0.25	1		0.25
0.99	0.02	1		0.02	-36.0	3.75	1		3.75
0.99	-0.02	-1	0.02		-31.5	5.50	1		5.50
0.95	-0.06	-1	0.06		-25.0	7.00	1		7.00
0.87	-0.10	-1	0.10		-17.5	7.25	1		7.25
0.74	-0.14	-1	0.14		-10.5	6.25	1		6.25
0.59	-0.17	-1	0.17		-5.0	6.00	1		6.00
0.41	-0.19	-1	0.19		1.5	6.25	1		6.25
0.21	-0.20	-1	0.20		7.5	5.75	1		5.75
0.00	-0.21	-1	0.21		13.0	5.75	1		5.75
-0.21	-0.20	-1	0.20		19.0	5.75	1		5.75
-0.41	-0.19	-1	0.19		24.5	5.75	1		5.75
-0.59	-0.17	-1	0.17		30.5	5.75	1		5.75
-0.74	-0.14	-1	0.14		36.0	5.75	1		5.75
-0.87	-0.10	-1	0.10		42.0	6.00	1		6.00
-0.95	-0.06	-1	0.06		48.0	5.75	1		5.75
-0.99	-0.02	-1	0.02		53.5	4.50	1		4.50
-0.99	0.02	1		0.02	57.0	2.00	1		2.00
-0.95	0.06	1		0.06	57.5	-0.75	-1	0.75	
-0.87	0.10	1		0.10	55.5	-3.00	-1	3.00	
-0.74	0.14	1		0.14	51.5	-5.00	-1	5.00	
-0.59	0.17	1		0.17	45.5	-6.75	-1	6.75	
-0.41	0.19	1		0.19	38.0	-8.00	-1	8.00	
-0.21	0.20	1		0.20	29.5	-9.25	-1	9.25	
Sum	0.00	Sum of	1.99	1.99		0.00	Sum of	95.00	95.00
		Frames	15	15			Frames	12	18
		Average	0.13	0.13			Average	7.92	5.28
			VIA	0.00				VIA	2.64

ACCELERATION INDEX OF ASYMMETRY (AIA)

Figure 16 on the left depicts the accelerations associated to forward and backward motion correspondent to the motion of an animated ideal simple physical pendulum. A way to measure symmetry/asymmetry in acceleration for this system is calculating |average acceleration when moving forwards - average acceleration when moving backwards|. If these averages coincide, it means there is no difference between the magnitudes of forward and backward accelerations. We will call this difference Acceleration Index of Asymmetry (AIA). In the case of the pendulum its value equals zero and we may conclude that this system is perfectly symmetric when comparing its forward and backward accelerations.

Figure 16 on the right depicts the accelerations associated to forward and backward motion correspondent to the motion of the human left ankle in animated human walking as if on a treadmill. The AIA = 0.975. In general; if AIA = 0, there is perfect symmetry between the forward and backward average accelerations; if AIA > 0, there is asymmetry and the system under study on average moves forward and backward with different accelerations.

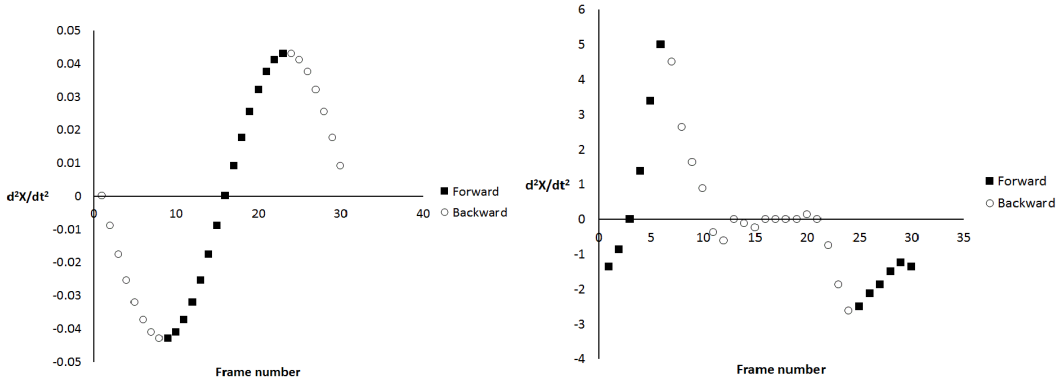

Figure 16. **Left. Horizontal accelerations d^2X/dt^2 of a dot correspondent to the center of mass of an ideal simple physical pendulum oscillating between 20° and -20°. Right. Horizontal accelerations d^2X/dt^2 of a dot correspondent to the motion of a left ankle in human walking as if on a treadmill. For both systems the number of frames correspondent to the total number of depicted horizontal accelerations is 30.**

Table 4 depicts the detailed calculations of the AIA for the cases of the pendulum and the human ankle. Notice that the sums of accelerations for each case correspond to forward or backward motion which has been determined before by the signs of velocities.

In synthesis we have now two ways to measure the symmetry/asymmetry of the direction of horizontal motion using the VIA and the AIA indices. If an index equals zero,

the correspondent average physical magnitudes for forward and backward motion are perfectly symmetrical.

Table 4

Analysis of the symmetry/asymmetry between forward and backward average accelerations of an ideal simple physical pendulum and of the left ankle in human walking as if on a treadmill. X: horizontal position; d^2X/dt^2: horizontal acceleration; Sign: sign of horizontal velocity; FA: forward acceleration; BV: backward acceleration.

Ideal periodic motion					Left ankle in human walking				
X	d^2X/dt^2	Sign	FA	BA	X	d^2X/dt^2	Sign	FA	BA
0.00	0.00	1		0.00	19.5	-1.38	-1	1.38	
0.21	-0.01	1		0.01	8.0	-0.88	-1	0.88	
0.41	-0.02	1		0.02	-4.5	0.00	-1	0	
0.59	-0.02	1		0.02	-17.0	1.38	-1	1.38	
0.74	-0.03	1		0.03	-28.5	3.38	-1	3.38	
0.87	-0.04	1		0.04	-36.5	5.00	-1	5.00	
0.95	-0.04	1		0.04	-39.0	4.50	1		4.50
0.99	-0.04	1		0.04	-36.0	2.62	1		2.62
0.99	-0.04	-1	0.04		-31.5	1.62	1		1.62
0.95	-0.04	-1	0.04		-25.0	0.88	1		0.88
0.87	-0.04	-1	0.04		-17.5	-0.38	1		0.38
0.74	-0.03	-1	0.03		-10.5	-0.62	1		0.62
0.59	-0.02	-1	0.02		-5.0	0.00	1		0.00
0.41	-0.02	-1	0.02		1.5	-0.12	1		0.12
0.21	-0.01	-1	0.01		7.5	-0.25	1		0.25
0.00	0.00	-1	0.00		13.0	0.00	1		0.00
-0.21	0.01	-1	0.01		19.0	0.00	1		0.00
-0.41	0.02	-1	0.02		24.5	0.00	1		0.00
-0.59	0.02	-1	0.02		30.5	0.00	1		0.00
-0.74	0.03	-1	0.03		36.0	0.12	1		0.12
-0.87	0.04	-1	0.04		42.0	0.00	1		0.00
-0.95	0.04	-1	0.04		48.0	-0.75	1		0.75
-0.99	0.04	-1	0.04		53.5	-1.88	1		1.88
-0.99	0.04	-1		0.04	57.0	-2.62	1		2.62
-0.95	0.04	-1		0.04	57.5	-2.50	-1	2.50	
-0.87	0.04	-1		0.04	55.5	-2.12	-1	2.12	
-0.74	0.03	-1		0.03	51.5	-1.88	-1	1.88	
-0.59	0.02	1		0.02	45.5	-1.50	-1	1.50	
-0.41	0.02	1		0.02	38.0	-1.25	-1	1.25	
-0.21	0.01	1		0.01	29.5	-1.38	-1	1.38	
Sum	0.00		0.41	0.41	Sum	0.00		22.63	16.38
		Frames	15	15			Frames	12	18
		Average	0.03	0.03			Average	1.89	0.91
			AIA	0.00				AIA	0.98

If an index is greater than zero, the analyzed physical magnitude is not symmetrical. Hence, the direction of horizontal motion has at least two essential components for potential analysis: the direction of velocity and the direction of acceleration.

PHASE PORTRAIT INDEX OF ASYMMETRY (PPIA)

Figure 17 on the left depicts simultaneously the magnitudes of the forward and backward positions and velocities we have calculated for the animated ideal simple physical pendulum. The horizontal axis is the dimension correspondent to the horizontal position X and the vertical axis the dimension correspondent to the horizontal velocity dX/dt or V. The Euclidean distance between the coordinates correspondent to any pair of dots n+1 and n depicted in the figure may be defined mathematically as:

$$\text{Distance} = \sqrt{(\mathbf{X_{n+1}} - \mathbf{X_n})^2 + (\mathbf{V_{n+1}} - \mathbf{V_n})^2}$$

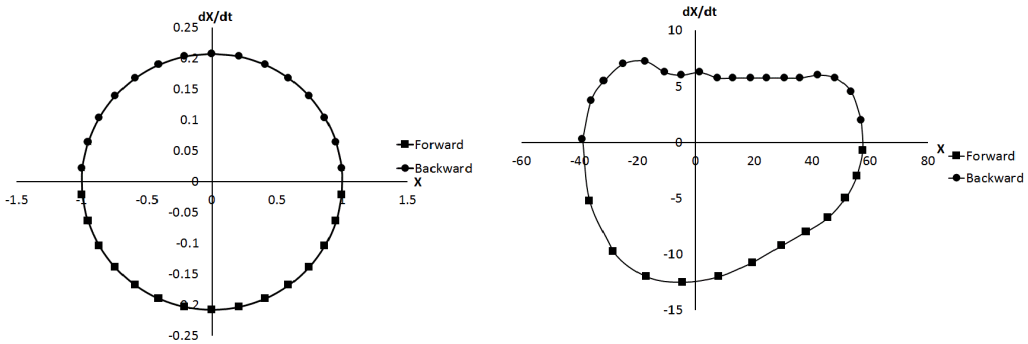

Figure 17. **Left. Phase portrait representation of horizontal position and velocity for the ideal simple physical pendulum example. Right. Phase portrait representation of horizontal position and velocity for the left ankle in human walking as if on the treadmill example.**

This distance is defined using the forward differences $\mathbf{X_{n+1}} - \mathbf{X_n}$ which may be understood as velocities and the forward differences $\mathbf{V_{n+1}} - \mathbf{V_n}$ which may be understood as accelerations between any pair of two sequential coordinates, as $\mathbf{t_{n+1}} - \mathbf{t_n}$ is constant for any value of n and without loss of generality may be normalized to one. This graphical representation using positions and velocities is known as a phase portrait representation and the plane where it is represented is known as a phase plane (Alligood et al., 1997). We may state then that the distance between any pair of two sequential coordinates in a phase portrait figure, carries information about velocity and acceleration. Even, we may use instead of forward differences, central differences as we did for the calculation of VIA and AIA in order to obtain PPIA values.

Table 5

Analysis of the symmetry/asymmetry between forward and backward motions of an animated ideal simple physical pendulum and of the left ankle in animated human walking as if on the treadmill using phase portrait representation. X: horizontal position; dX/dt: horizontal velocity; d^2X/dt^2: horizontal acceleration; Sign: sign of horizontal velocity; FPP: forward phase portrait; BFP: backward phase portrait.

Ideal periodic motion						Left ankle in human walking					
X	dX/dt	d^2X/dt^2	Sign	FPP	BPP	X	dX/dt	d^2X/dt^2	Sig	FPP	BPP
0.00	0.21	0.00	1		0.21	19.5	-10.75	-1.38	-1	10.84	
0.21	0.20	-0.01	1		0.20	8.0	-12.00	-0.88	-1	12.03	
0.41	0.19	-0.02	1		0.19	-4.5	-12.50	0.00	-1	12.50	
0.59	0.17	-0.02	1		0.17	-17.0	-12.00	1.38	-1	12.08	
0.74	0.14	-0.03	1		0.14	-28.5	-9.75	3.38	-1	10.32	
0.87	0.10	-0.04	1		0.11	-36.5	-5.25	5.00	-1	7.25	
0.95	0.06	-0.04	1		0.08	-39.0	0.25	4.50	1		4.51
0.99	0.02	-0.04	1		0.05	-36.0	3.75	2.62	1		4.58
0.99	-0.02	-0.04	-1	0.05		-31.5	5.50	1.62	1		5.74
0.95	-0.06	-0.04	-1	0.08		-25.0	7.00	0.88	1		7.05
0.87	-0.10	-0.04	-1	0.11		-17.5	7.25	-0.38	1		7.26
0.74	-0.14	-0.03	-1	0.14		-10.5	6.25	-0.62	1		6.28
0.59	-0.17	-0.02	-1	0.17		-5.0	6.00	0.00	1		6.00
0.41	-0.19	-0.02	-1	0.19		1.5	6.25	-0.12	1		6.25
0.21	-0.20	-0.01	-1	0.20		7.5	5.75	-0.25	1		5.76
0.00	-0.21	0.00	-1	0.21		13.0	5.75	0.00	1		5.75
-0.21	-0.20	0.01	-1	0.20		19.0	5.75	0.00	1		5.75
-0.41	-0.19	0.02	-1	0.19		24.5	5.75	0.00	1		5.75
-0.59	-0.17	0.02	-1	0.17		30.5	5.75	0.00	1		5.75
-0.74	-0.14	0.03	-1	0.14		36.0	5.75	0.12	1		5.75
-0.87	-0.10	0.04	-1	0.11		42.0	6.00	0.00	1		6.00
-0.95	-0.06	0.04	-1	0.08		48.0	5.75	-0.75	1		5.80
-0.99	-0.02	0.04	-1	0.05		53.5	4.50	-1.88	1		4.88
-0.99	0.02	0.04	1		0.05	57.0	2.00	-2.62	1		3.30
-0.95	0.06	0.04	1		0.08	57.5	-0.75	-2.50	-1	2.61	
-0.87	0.10	0.04	1		0.11	55.5	-3.00	-2.12	-1	3.68	
-0.74	0.14	0.03	1		0.14	51.5	-5.00	-1.88	-1	5.34	
-0.59	0.17	0.02	1		0.17	45.5	-6.75	-1.50	-1	6.92	
-0.41	0.19	0.02	1		0.19	38.0	-8.00	-1.25	-1	8.10	
-0.21	0.20	0.01	1		0.20	29.5	-9.25	-1.38	-1	9.35	
Sum	0.000	0.00		2.09	2.09		0.0	0.00		101.01	102.15
			Fra	15	15				Fra	12	18
			Aver	0.14	0.14				Av	8.42	5.68
				PPIA	0.00					PPIA	2.74

We define the Phase Portrait Index of Asymmetry (PPIA) as |average distance when moving forwards - average distance when moving backwards| in the phase portrait graph. Notice that these distances are used because they contain the information correspondent to velocity and acceleration. Not surprisingly, after having found before perfect symmetry using VIA and AIA indexes, PPIA equals zero for the pendulum (see Table 5). This value

may be interpreted as perfect symmetry as we did for the analysis of symmetry/asymmetry in the direction of motion using velocities and accelerations.

Figure 17 on the right depicts simultaneously the magnitudes of the forward and backward positions and velocities that we have calculated for the left ankle in animated human walking as if on the treadmill. The apparent asymmetry depicted in the figure corresponds to a PPIA = 2.74 (see Table 5).

An inspection of the patterns in Figure 17 and the previous definitions of TIA and VIA suffice to read and calculate these indices directly from the graph. Indeed, similarly as in previous graphical representations for velocity, a dot below the horizontal axis has forward motion and a dot above the horizontal axis has backward motion. For the case of the ankle, the number of dots below the horizontal axis is 12 and above 18.

To summarize, the indexes and the phase portrait figure together offer the following information: First, the amount of time spent by an animation moving either forwards or backwards (by multiplying the number of dots either below or above the horizontal line of the phase portrait times the duration of each frame) and the asymmetry between the duration of forward and backward motions (by calculating the TIA index). Second, the asymmetry between the average velocities when moving forwards and backwards (by calculating the VIA index). Third, the asymmetry between the average accelerations when moving forwards and backwards (by calculating the AIA index). Fourth, the asymmetry between the average velocities estimable from the visual inspection of the horizontal components of the phase portrait figure above and below the horizontal axis. Fifth, the asymmetry between the average accelerations estimable from the visual inspection of the vertical components of the phase portrait figure above and below the horizontal axis. Sixth, a measurement of overall asymmetry calculating the PPIA or inspecting the symmetry of the phase portrait figure comparing the curves above and below the horizontal axis, both including the contribution of velocities and accelerations of individual dots.

APPLICATION OF THE PHASE PORTRAIT TECHNIQUES TO THE ANALYSIS OF THE DIRECTION OF HORIZONTAL MOTION IN HUMAN ACTIONS

The goal of this section is to test whether the techniques developed in the previous section can be applied to explain performance in the experiments reported in Chapter 3. For each of the four actions used in the previous experiments, first we analyze the individual physical properties of the points that comprise each action using the phase portrait tools, second at the level of individual dots we analyze the potential causality between their physical properties and correspondent performance in the experiments, third at the level of individual dots we analyze the association between physical properties and performance.

PHASE PORTRAIT ANALYSIS OF INDIVIDUAL JOINTS IN THE ANIMATED HUMAN WALKER

We stated in the previous section, that the PPIA may be used to measure the overall asymmetry of the direction of articulated motion. To obtain PPIA we first calculated the Euclidean distance between sequential coordinates across the set of 30 frames that comprise the walking animation, summed independently those correspondent to forward motion and backward motion, averaged them and finally used these averages to get the PPIA. As these coordinates contain information about the velocity and acceleration of a particular dot from frame to frame and this information was used to get the VIA and AIA for the full set of 30 frames, we may approximate the PPIA value using VIA and AIA indexes as follows:

$$\widetilde{PPIA} \cong \sqrt{VIA^2 + AIA^2}$$

Table 6 depicts VIA, AIA $\widetilde{\text{PPIA}}$ and PPIA for each of the thirteen joints that comprise the walking animation. As Experiment 2 described in Chapter 3 used the walking animation oriented in profile, frontal, and rotated points of view, we show the indexes for each of the four orientations.

Table 6

Phase portrait indexes for the lower walker animation in profile, 30°, 60°, and frontal orientation. LW: Left wrist. LE: Left elbow. LS: Left shoulder. RW: Right wrist. RE: Right elbow. RS: Right shoulder. LA: Left ankle. LK: Left knee. LH: Left hip. RA: Right ankle. RK: Right knee. RH: Right hip.

Profile					30°				
Joint	VIA	AIA	$\widetilde{\text{PPIA}}$	PPIA	Joint	VIA	AIA	$\widetilde{\text{PPIA}}$	PPIA
LA	2.64	0.98	2.81	2.74	LA	2.31	0.80	2.45	2.38
LK	0.10	0.01	0.10	0.10	LK	0.05	0.00	0.05	0.06
LH	0.00	0.02	0.02	0.00	LH	0.00	0.06	0.06	0.03
RA	2.64	0.95	2.81	2.75	RA	1.47	1.21	1.91	2.05
RK	0.05	0.02	0.05	0.05	RK	0.04	0.03	0.04	0.02
RH	0.00	0.00	0.00	0.01	RH	0.35	0.02	0.36	0.30
LW	0.08	0.17	0.18	0.18	LW	0.07	0.08	0.10	0.14
LE	0.52	0.23	0.57	0.61	LE	0.50	0.18	0.53	0.55
LS	0.06	0.01	0.06	0.05	LS	0.05	0.00	0.05	0.03
RW	1.10	0.28	1.14	1.19	RW	0.98	0.26	1.02	1.06
RE	0.52	0.23	0.57	0.61	RE	0.61	0.20	0.64	0.67
RS	0.06	0.06	0.08	0.06	RS	0.05	0.09	0.10	0.11
H	1.10	0.29	1.14	1.18	H	0.93	0.22	0.95	0.99

Because $\widetilde{\text{PPIA}}$ has been defined as the Euclidean distance using VIA and AIA, the values of these approximations for each joint can be depicted on a two-dimensional orthogonal representation. Figure 18 depicts the allocations of the thirteen joints of the walking animation correspondent to different orientations. In the case of the walking animation, the ankles have VIA, AIA, and $\widetilde{\text{PPIA}}$ (distance to the origin) values greater than any other joint for frontal, 30°, and 60° orientations. These results suggest that these joints carry more information about the difference between forward and backward direction of motion than any other joint.

In order to explore the potential value of phase portrait indexes to explain performance in Experiment 2 of Chapter 3, we may try to correlate each of the indexes and performance.

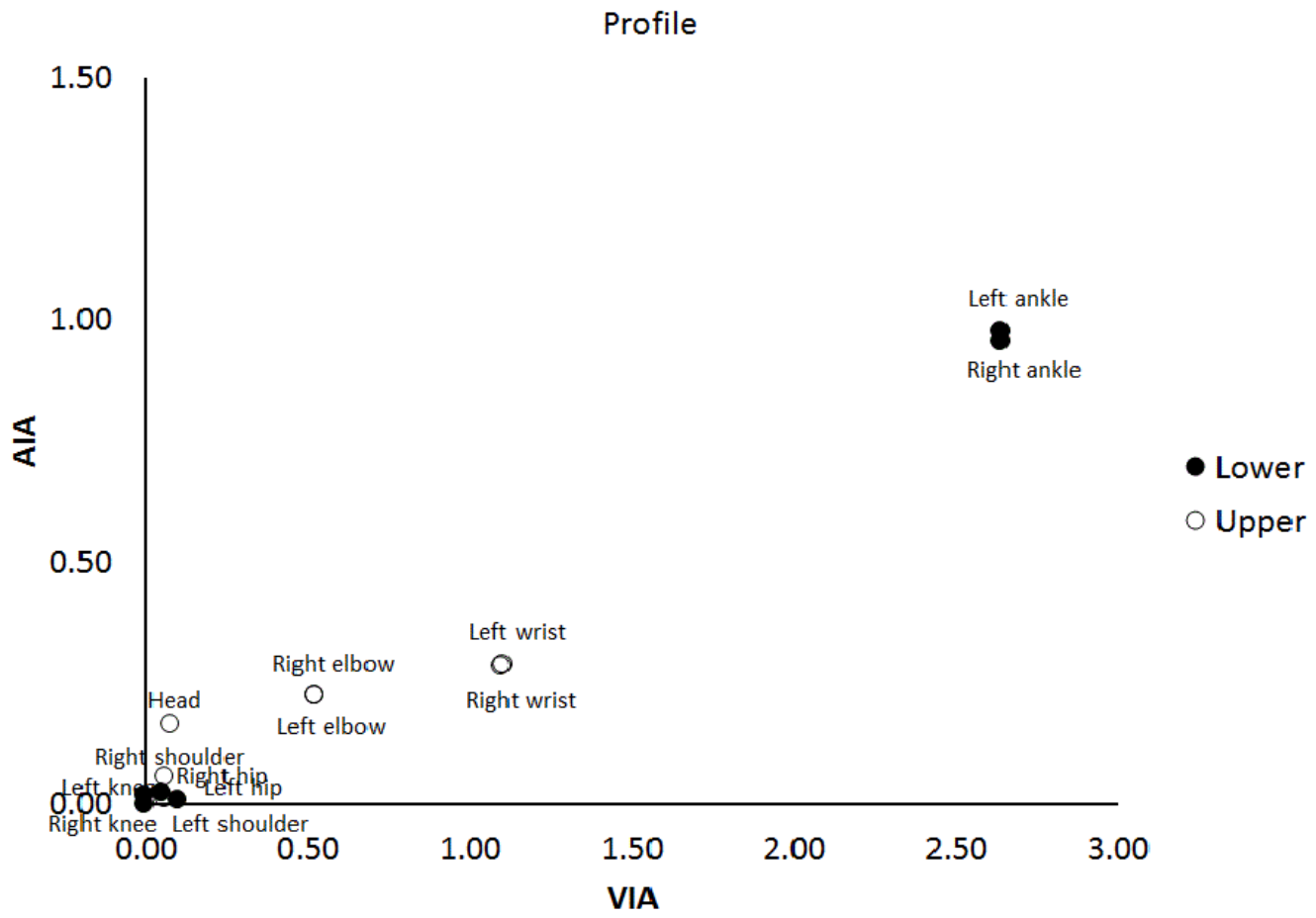

Figure 18. **Two-dimensional representations of VIA, AIA and $\widetilde{\text{PPIA}}$ for each of the thirteen joints that comprise the animated human walker stimulus: profile view.**

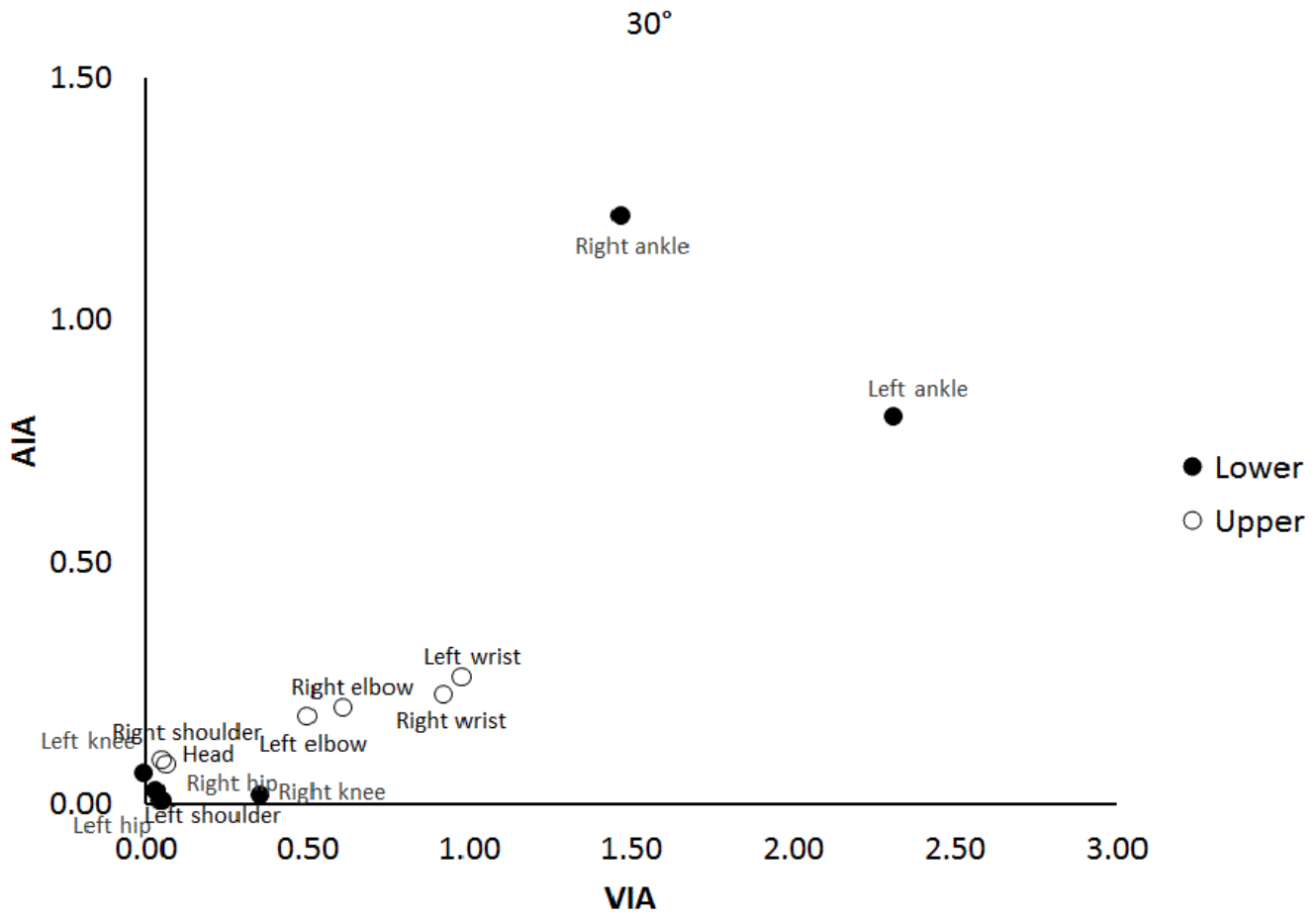

Figure 18. **Two-dimensional representations of VIA, AIA and $\widehat{\text{PPIA}}$ for each of the thirteen joints that comprise the animated human walker stimulus (continued): 30° view.**

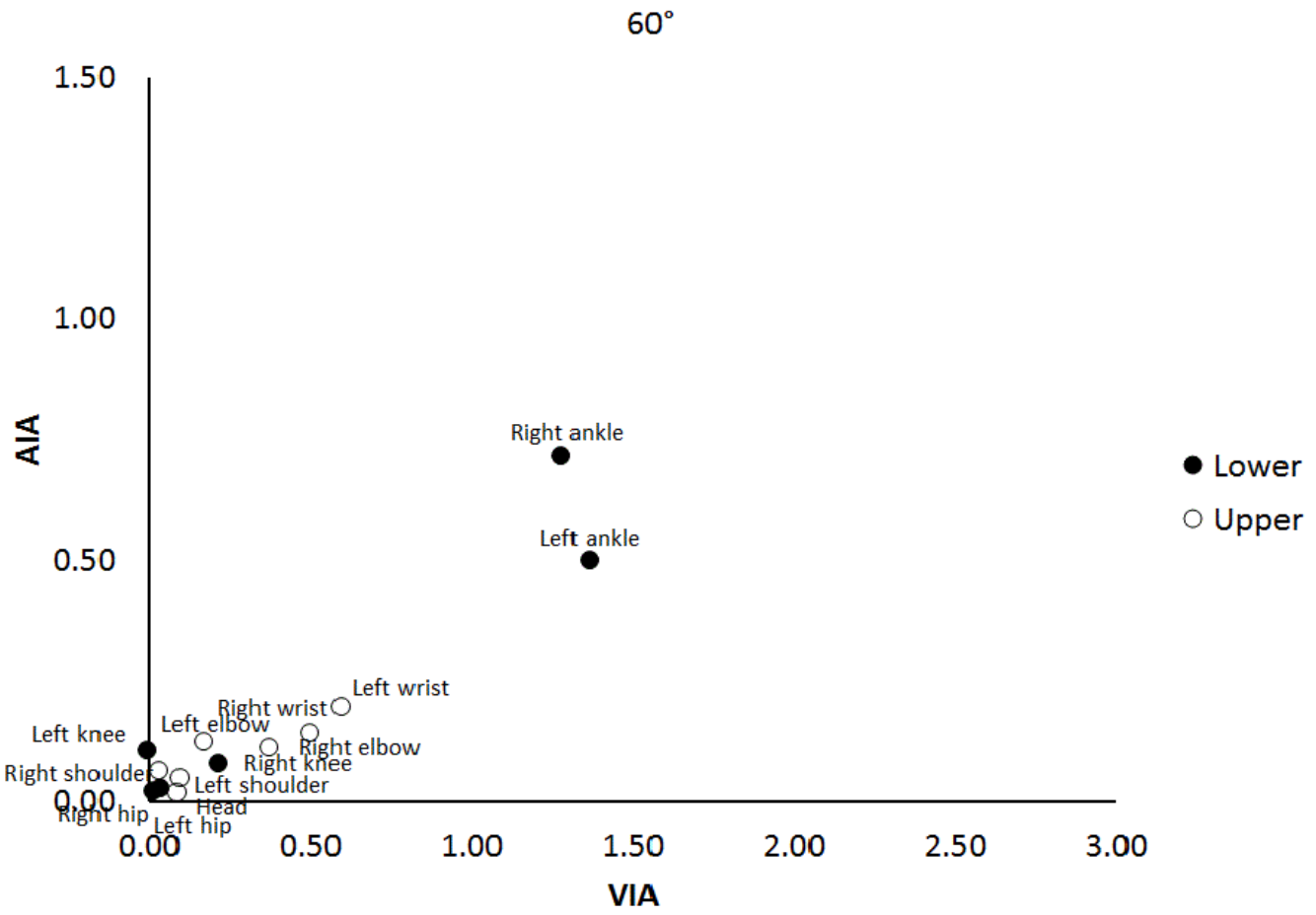

Figure 18. **Two-dimensional representations of VIA, AIA and $\widehat{\text{PPIA}}$ for each of the thirteen joints that comprise the animated human walker stimulus (continued): 60° view.**

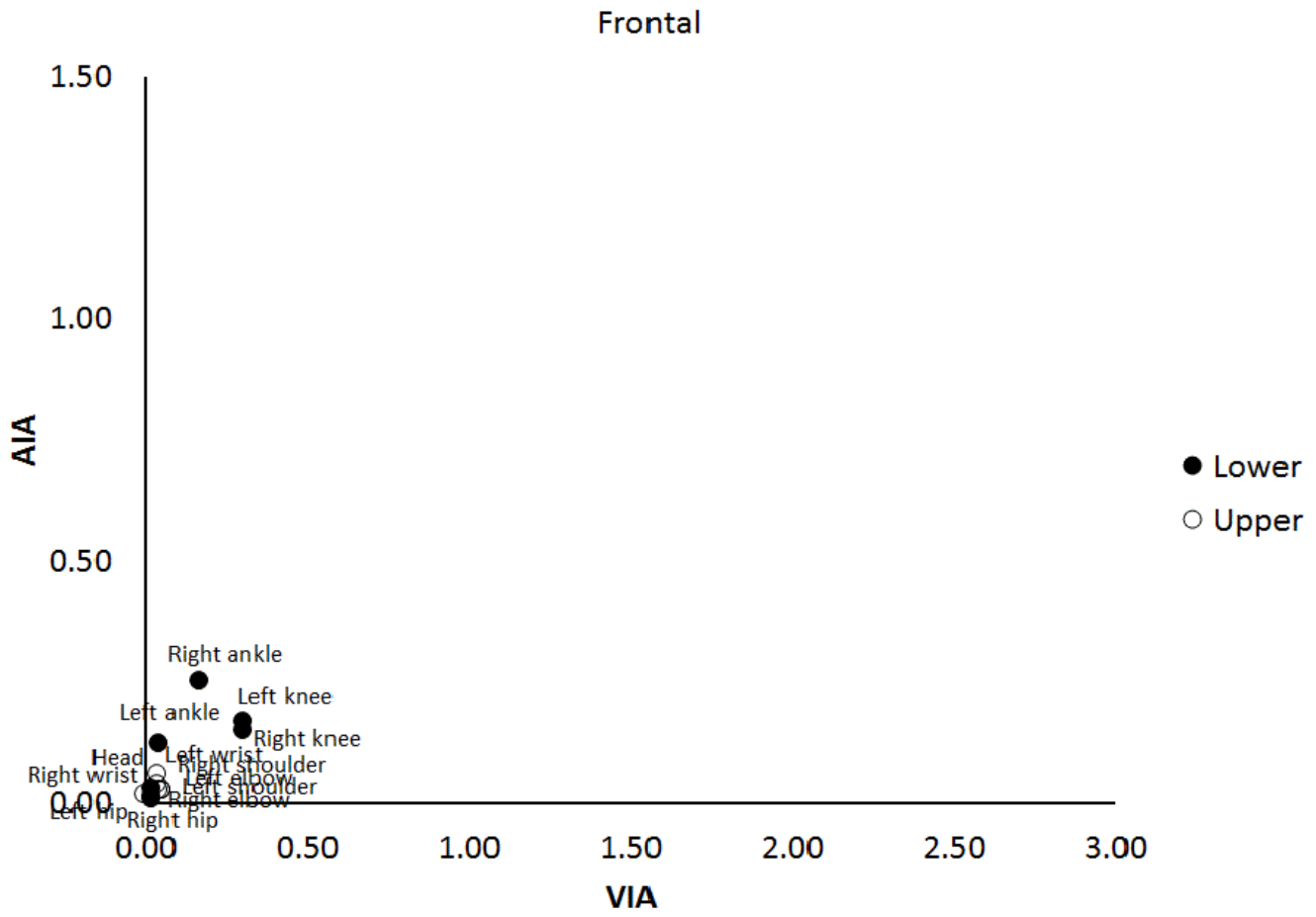

Figure 18. **Two-dimensional representations of VIA, AIA and $\widehat{\text{PPIA}}$ for each of the thirteen joints that comprise the animated human walker stimulus (continued): frontal view.**

Table 6

Phase portrait indexes for the lower walker animation in profile, 30°, 60°, and frontal orientation (continued). LW: Left wrist. LE: Left elbow. LS: Left shoulder. RW: Right wrist. RE: Right elbow. RS: Right shoulder. LA: Left ankle. LK: Left knee. LH: Left hip. RA: Right ankle. RK: Right knee. RH: Right hip

60°					Frontal				
Joint	VIA	AIA	$\widetilde{\text{PPIA}}$	PPIA	Joint	VIA	AIA	$\widetilde{\text{PPIA}}$	PPIA
LA	1.37	0.50	1.46	1.39	LA	0.05	0.12	0.13	0.16
LK	0.04	0.03	0.05	0.03	LK	0.02	0.03	0.03	0.04
LH	0.00	0.10	0.10	0.02	LH	0.31	0.17	0.35	0.37
RA	1.28	0.71	1.47	1.47	RA	0.17	0.25	0.30	0.35
RK	0.02	0.02	0.02	0.03	RK	0.02	0.01	0.02	0.01
RH	0.22	0.08	0.23	0.26	RH	0.31	0.15	0.34	0.36
LW	0.09	0.02	0.09	0.10	LW	0.04	0.03	0.05	0.01
LE	0.17	0.12	0.21	0.24	LE	0.05	0.03	0.06	0.03
LS	0.10	0.05	0.11	0.11	LS	0.00	0.02	0.02	0.01
RW	0.60	0.19	0.63	0.65	RW	0.04	0.06	0.07	0.07
RE	0.37	0.11	0.39	0.40	RE	0.05	0.03	0.06	0.03
RS	0.04	0.06	0.07	0.07	RS	0.02	0.01	0.03	0.02
H	0.50	0.14	0.52	0.55	H	0.04	0.04	0.06	0.06

Before starting the description of the procedure, it is important to stress that Pearson correlations may be used even if data are not normally distributed. Chok (2010) suggested that "Pearson's correlation could have significant advantages for continuous non-normal data which does not have obvious outliers. Thus, the shape of the distribution should not be a sole reason for not using the Pearson product moment correlation coefficient" (p. v). In the case of our data, values of kinematic indexes vary among joints and across orientations but not in an extreme way and performance measured with sensitivity varies between -3 and 3. As our data are psychophysical and have been generated under controlled conditions and cannot have obvious outliers after the considerations we have made, we conclude that it can be treated with Pearson correlations. The use of Pearson correlations is necessary to adapt Bland and Altman (1995) procedures in order to explore the contribution of individual dots to performance as it will be explained in the following paragraphs.

The main reason to use correlations and not regressions is the exploratory nature of the relationship between an index and performance: We're interested first in examining association of physical properties with performance by the analysis of physical properties of dots, and second we're interested in learning how strong or weak the associations are and the pattern, if any, they follow. Possible empirical explanations of performance based on the physical and psychophysical properties of dots that represent joints in animations of actions, would be considered in the final part of this chapter when discussing prospective development and application of the techniques we are about to introduce.

As the data of the experiment consist of repeated observations from several subjects, any explanation using correlational or regression techniques should take into account this repeated measures characteristic of data.

Bland and Altman (1995, p. 446) pointed out referring to correlations, that it could be highly misleading to analyze paired data when there is more than one observation per subject, by combining repeated observations from several subjects and then calculating the correlation coefficient as if the data were a simple sample. In a similar way to explanation of variance due to treatments/conditions or due to individual differences for repeated measures ANOVA, the authors developed a method to calculate correlations taking into account and distinguishing the contribution of individual differences from the contribution of variables under study in the association.

We adapted the procedures suggested by the authors to avoid erroneous interpretations and explored the contribution of individual joints to performance in Experiment 2 of Chapter 3. First, we used multiple linear regressions and ANOVA as Bland and Altman suggested, to obtain Pearson correlations between sensitivity and any of the three indexes (VIA, AIA, or PPIA) for each joint. Additional multiple linear models we will be introduced later in this chapter to explore the association between performance and kinematic information of multiple properties of single or groups of joints.

Table 7 shows the importance (amount of explained variance) for VIA, AIA, and PIA in Experiment 2 of Chapter 3 correspondent to the classification of the direction of articulated motion of the lower part of the body when walking. Three multiple linear models were built. In Model 1, we included VIA correspondent to the left ankle when it is shown as a part of the lower body animation, and 13 dummy variables to estimate the contribution of the 14 subjects who participated in the experiment, to the total variance of performance. The use of dummy variables in the analysis, enabled us to quantify and isolate the contribution of each participant. Models 2 and 3 included respectively AIA and PPIA, and both of them

the 13 dummy variables. Model 1 including VIA, explains 46.2 % of the total variance and VIA explains 27.1%, Model 2 including AIA, 43.8% of the total variance and AIA 24.7% and Model 3 including PPIA, 45.1% of the total variance and PPIA 26%. As the models have the same number of regressors, comparison among R^2 values suggest that Model 1 is more explanatory than Models 2 or 3.

Table 7

Importance of three explanatory models of performance in the classification of the direction of articulated motion of an animated lower walker using kinematic regressors correspondent to the left ankle. Performance corresponds to results reported in Chapter 3.

	Model 1	Model 2	Model 3
VIA	0.271		
AIA		0.247	
PPIA			0.260
Dummy1	0.006	0.006	0.006
Dummy2	0.006	0.006	0.006
Dummy3	0.006	0.006	0.006
Dummy4	0.012	0.012	0.012
Dummy5	0.006	0.006	0.006
Dummy6	0.004	0.004	0.004
Dummy7	0.006	0.006	0.006
Dummy8	0.007	0.007	0.007
Dummy9	0.025	0.025	0.025
Dummy10	0.002	0.002	0.002
Dummy11	0.006	0.006	0.006
Dummy12	0.032	0.032	0.032
Dummy13	0.073	0.073	0.073
R^2	0.462	0.438	0.451

Table 8 provides a standard presentation of the three models including values of estimated regressors and their significance. Despite the possibility of using regression models for prediction or estimation of regressors, we will be using them for calculation of importance and posterior calculation of correlations between regressors and performance.

Pearson correlation between VIA and performance measured by sensitivity d', may be calculated adapting the general formula proposed by Bland and Altman (1995). We get for our analysis:

$$r_{d'VIA} = \sqrt{\frac{\text{Sum of squares for VIA}}{\text{Sum of squares for VIA+Residual sum of squares}}}$$

Table 8

Specification of explanatory models of performance in the classification of the direction of articulated motion of an animated lower walker. Performance corresponds to results reported in Chapter 3.

	Model 1	Model 2	Model 3
Constant	2.71***	2.65***	2.69***
VIA	0.18***		
AIA		0.54***	
PPIA			0.18***
Dummy 1	-0.09	-0.09	-0.09
Dummy 2	-0.09	-0.09	-0.09
Dummy 3	-0.09	-0.09	-0.09
Dummy 4	0.00	0.00	0.00
Dummy 5	-0.46	-0.46	-0.46
Dummy 6	-0.40	-0.40	-0.40
Dummy 7	-0.09	-0.09	-0.09
Dummy 8	-0.48	-0.48	-0.48
Dummy 9	-0.69	-0.69	-0.69
Dummy 10	-0.20	-0.20	-0.20
Dummy 11	-0.09	-0.09	-0.09
Dummy 12	-0.75	-0.75	-0.75
Dummy 13	-1.00*	-1.00*	-1.00*
R^2	0.46	0.44	0.45
Adjusted R^2	0.28	0.25	0.27
F	2.52*	2.29*	2.42*

*p<.05. **p<.01. ***p<.001.

This formula uses sum of squares from Type III ANOVA for the correspondent regression, removes the variation due to subjects, and expresses the variation in d' due to

VIA as a Pearson correlation. We get in Model 2 for the association between sensitivity and VIA when the lower walker is shown $r_{d`VIA} = 0.58$ with $p < .001$.

Figure 19 depicts the coordinates of the joints that belong to the lower body (represented by filled circles) and the upper body (represented by unfilled circles) in a two-dimensional coordinate system correlation space where the horizontal coordinate represents the *Pearson correlation of VIA and sensitivity* and the vertical coordinate the *Pearson correlation of AIA and sensitivity* for the joints that belong to the lower or upper walker stimulus. This figure depicts the correlations calculated from the two multiple linear models including VIA or AIA, and their ANOVAs applying the procedures suggested by Bland and Altman (1995). The figure corresponds to the analysis of the isolated presentation of body parts (upper and lower walker conditions). As we are interested in comparing the magnitudes of association correspondent to all joints, we depict both significant and non-significant correlations paying attention to their magnitudes.

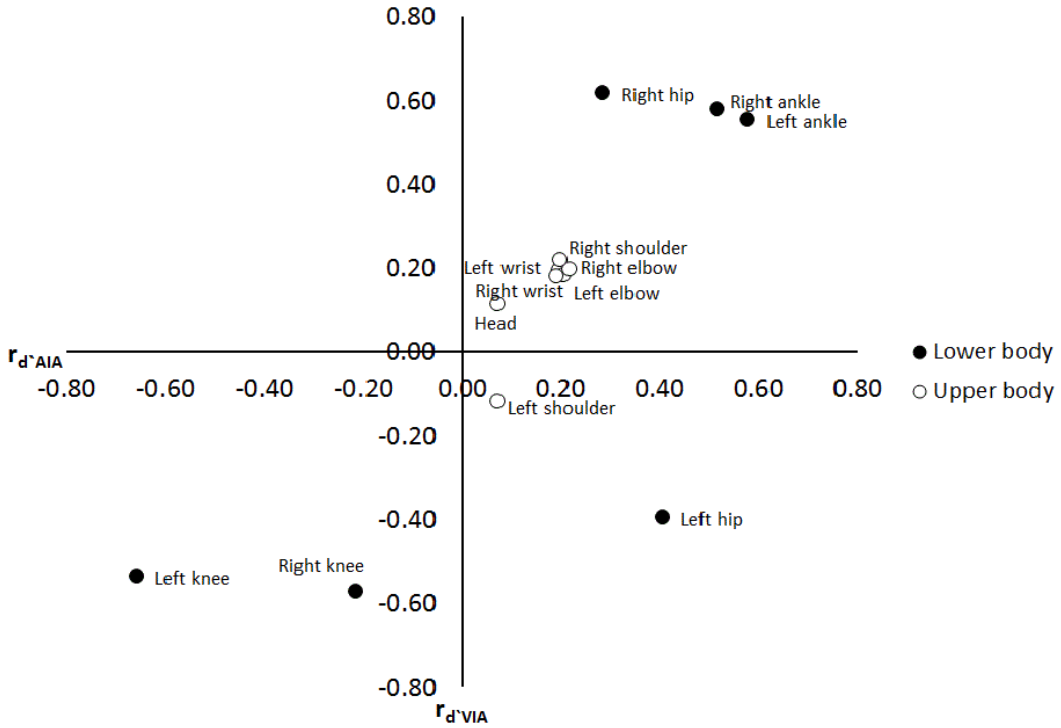

Figure 19. **Two-dimensional representations of correlations between VIA and sensitivity ($r_{d`VIA}$) and between AIA and sensitivity ($r_{d`AIA}$) for each of the thirteen joints that comprise the animated human walker stimulus. The figure corresponds to the analysis of isolated presentations of body parts using multiple linear models including VIA or AIA.**

A visual inspection for each joint, of the distances to the horizontal and vertical axis and to the origin of the frame of reference (a way to visualize the whole phase portrait contribution because the distance to the origin of the frame of reference carries information about the correlation between performance and VIA and about the correlation between performance and AIA), suggests that coordinates correspondent to the upper body joints are closer to the origin than coordinates correspondent to the lower body joints when these body parts are presented isolated. Inspection of these findings suggests the existence of distinctive patterns in the way the visual system uses kinematic information on asymmetry of the direction of articulated motion when analyzing different body parts of the walking animation: As correlations between performance and kinematic indexes are greater for the lower part than for the upper part, more kinematic information might be being used for the analysis of the lower part and less for the upper part, probably because availability of more information of direction of articulatory motion for the lower part.

PHASE PORTRAIT ANALYSIS OF THE ANIMATED HUMAN CRAWLER

Figure 20 depicts the allocations on a two-dimensional orthogonal representation of the thirteen joints of the crawling animation correspondent to different orientations. In the case of this animation, VIA, AIA, and $\widehat{PPIA}$ (distance to the origin) values for wrists, elbows, ankles, and knees configure a distinctive cluster when compared with homologous values correspondent to shoulders, hips, and head for frontal and 30° orientations (with values correspondent to upper joints a bit higher).These results suggest that joints that belong to the upper part of the body (wrists and elbows) or the lower part (ankles and knee) carry a similar amount of kinematic information about the difference between forward and backward direction of motion for the above mentioned orientations.

Figure 21 depicts the coordinates of the joints that belong to the lower body (represented by filled circles) and the upper body (represented by unfilled circles) in a two-dimensional coordinate system correlation space of the type described above for the phase portrait analysis of the human walker. Similarly to what we have explained before, the figure corresponds to the analysis of isolated presentation of body parts (upper and lower crawler conditions).

Inspection of the figure suggests different amounts of using of kinematic information on asymmetry of the direction of articulated motion by the joints irrespective of being lower or upper. For instance, right elbow perception might involve more use of acceleration information than left ankle perception and less use of velocity, and left wrist perception

might involve more use of velocity and acceleration information than right elbow perception. Similarly to the walking action, the use of information seems to be associated to its availability.

Figure 20. **Two-dimensional representations of VIA, AIA and $\widehat{\text{PPIA}}$ for each of the thirteen joints that comprise the animated human crawler stimulus: profile view.**

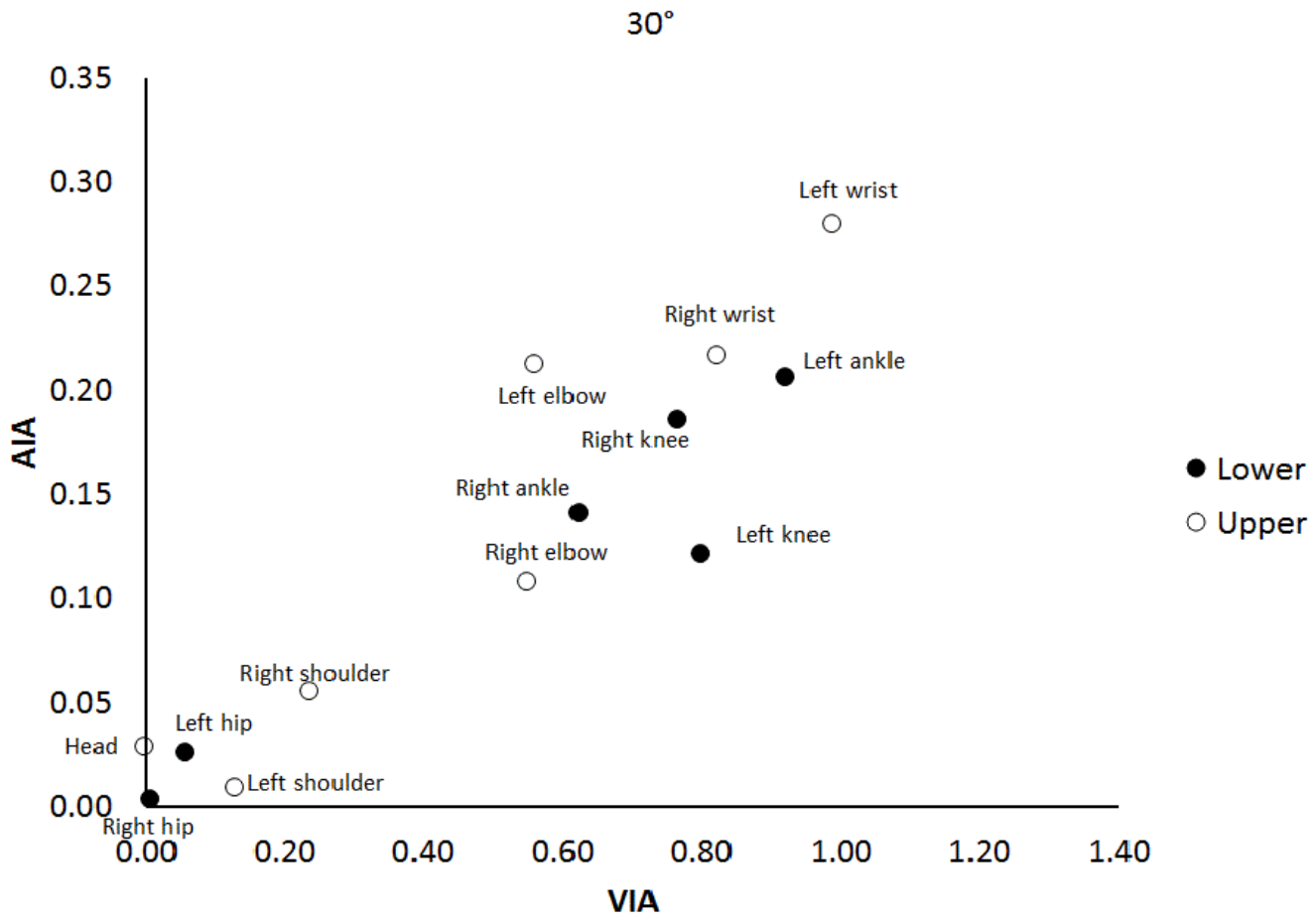

Figure 20. **Two-dimensional representations of VIA, AIA and $\widehat{\text{PPIA}}$ for each of the thirteen joints that comprise the animated human crawler stimulus (continued): 30° view.**

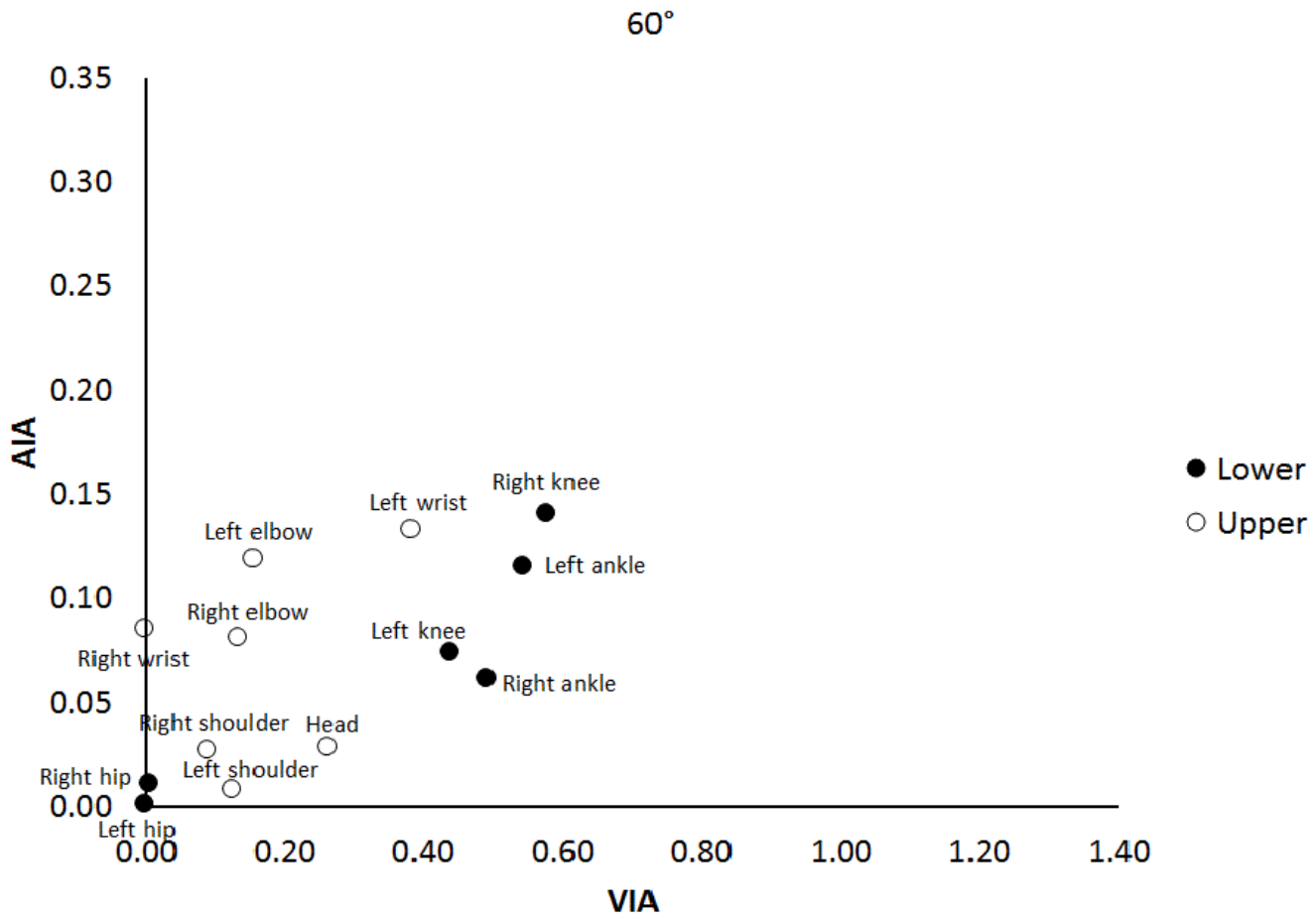

Figure 20. **Two-dimensional representations of VIA, AIA and $\widehat{\text{PPIA}}$ for each of the thirteen joints that comprise the animated human crawler stimulus (continued): 60° view.**

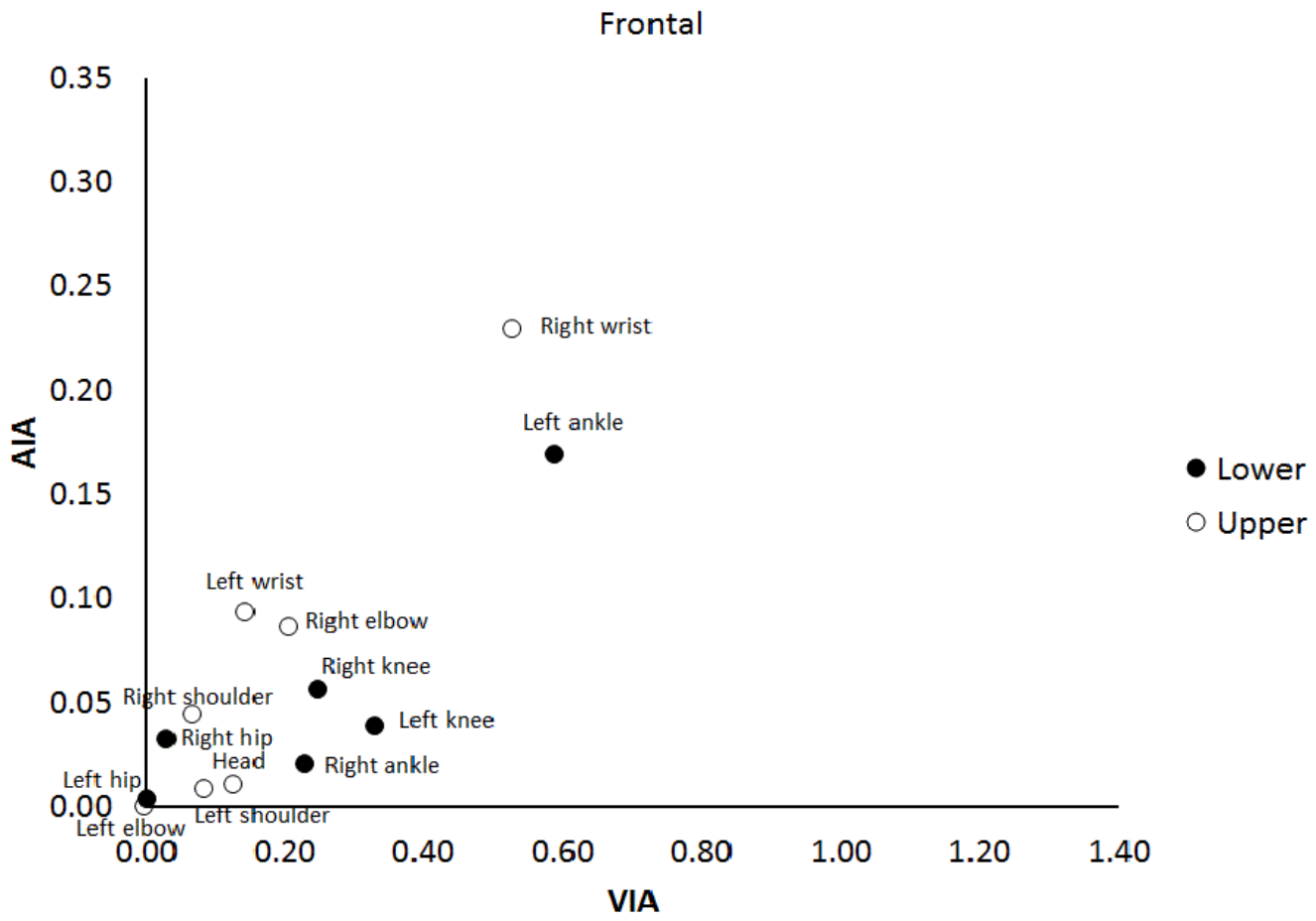

Figure 20. **Two-dimensional representations of VIA, AIA and $\widehat{\text{PPIA}}$ for each of the thirteen joints that comprise the animated human crawler stimulus (continued): frontal view.**

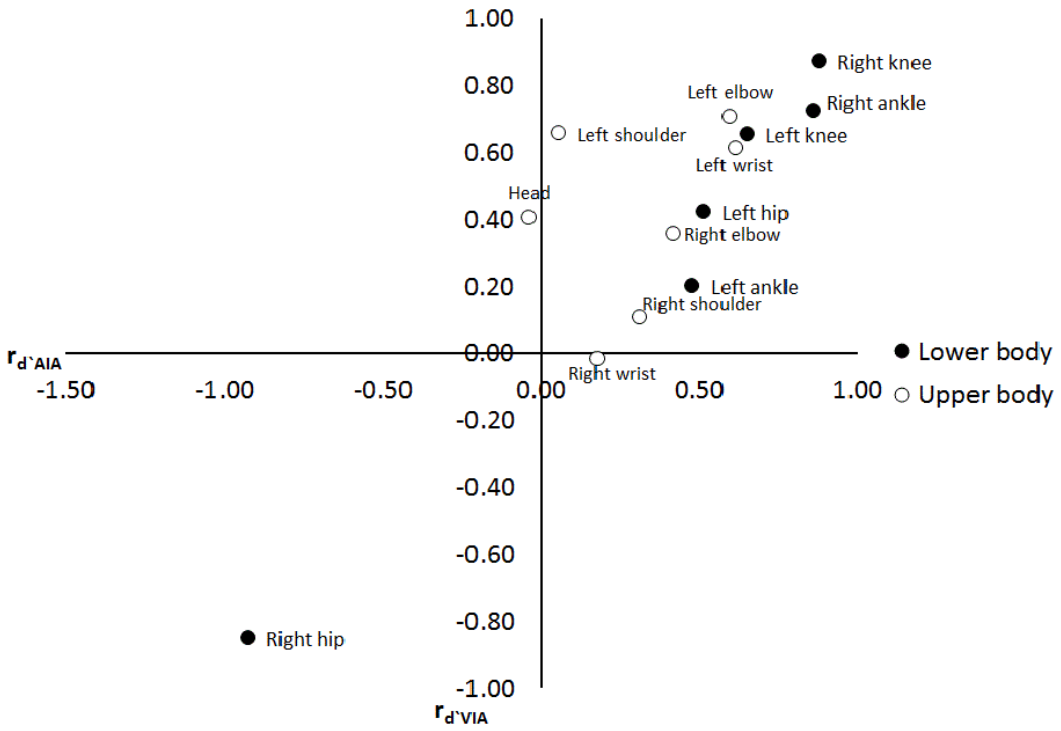

Figure 21. **Two-dimensional representations of correlations between VIA and sensitivity ($r_{d`VIA}$) and between AIA and sensitivity ($r_{d`AIA}$) for each of the thirteen joints that comprise the animated human crawler stimulus. The figure corresponds to the analysis of isolated presentations of body parts using multiple linear models including VIA or AIA.**

PHASE PORTRAIT ANALYSIS OF THE ANIMATED HUMAN HAND WALKER

Figure 22 depicts the allocations on a two-dimensional orthogonal representation of the thirteen joints of the walking animation correspondent to different orientations. In the case of the hand walking animation, wrists and elbows have VIA, AIA, and $\widetilde{PPIA}$ (distance to the origin) values greater than any other joint for profile, 30°, 60°, and even the frontal orientation. These results suggest that these joints carry more kinematic information about the difference between forward and backward direction of motion than other joints.

Inspection of Figure 23 suggests the existence of distinctive patterns in the way the visual system uses kinematic information on asymmetry of the direction of articulated motion when analyzing different body parts of the hand walking animation: More kinematic information is used for the analysis of the upper part and less for the lower part.

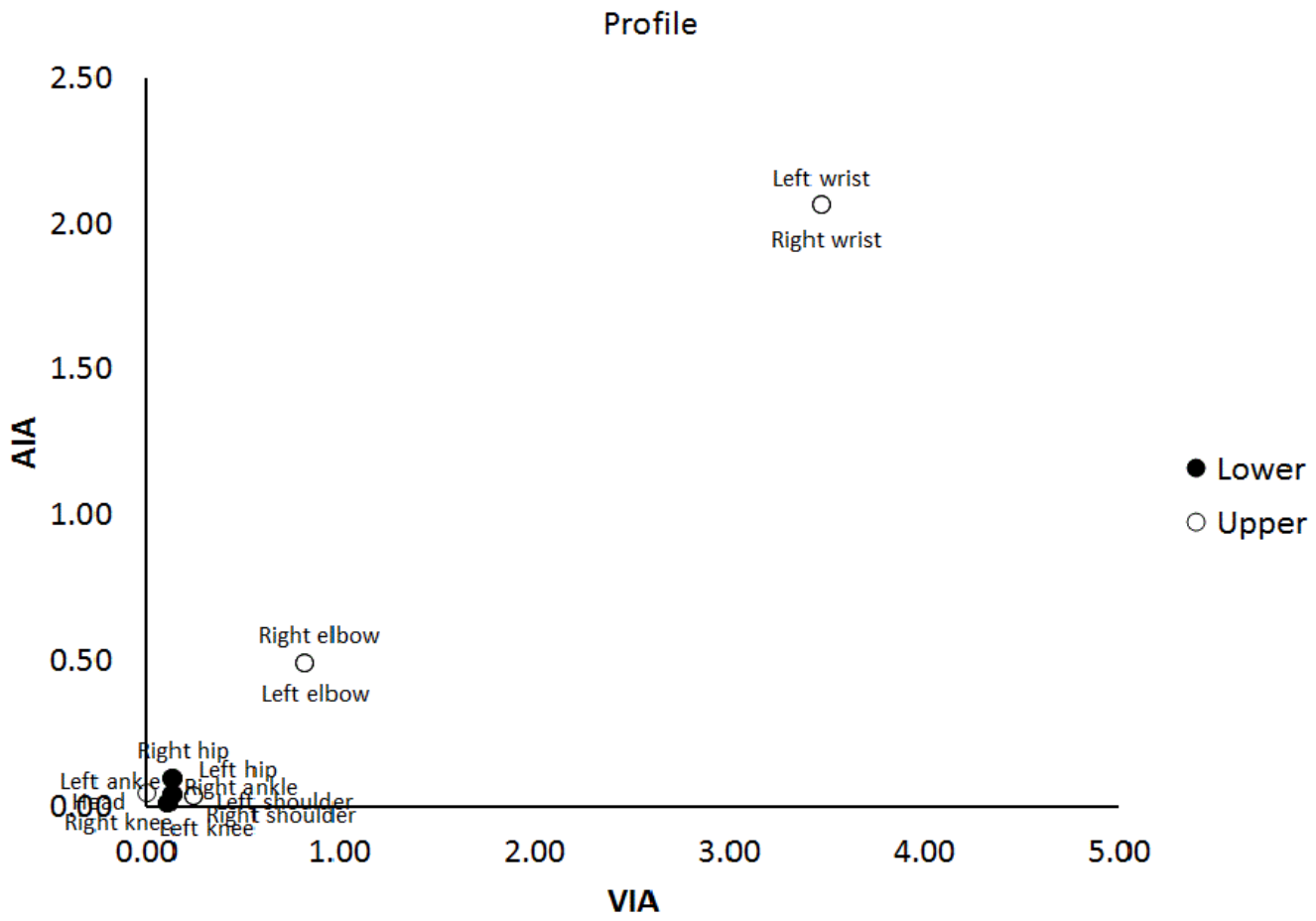

Figure 22. **Two-dimensional representations of VIA, AIA and $\widehat{\text{PPIA}}$ for each of the thirteen joints that comprise the animated hand walker stimulus: profile view.**

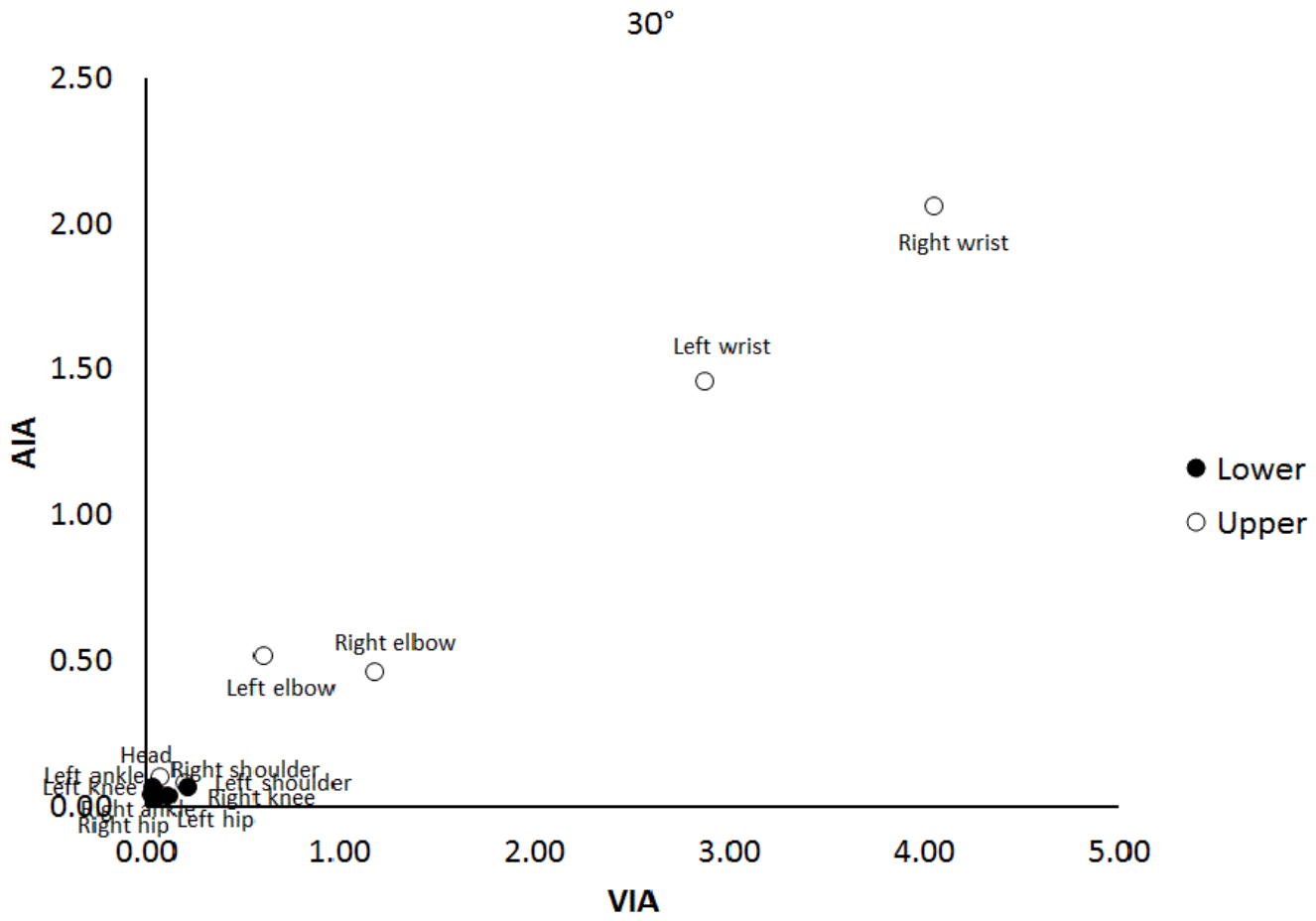

Figure 22. **Two-dimensional representations of VIA, AIA and $\widehat{\text{PPIA}}$ for each of the thirteen joints that comprise the animated hand walker stimulus (continued): 30° view.**

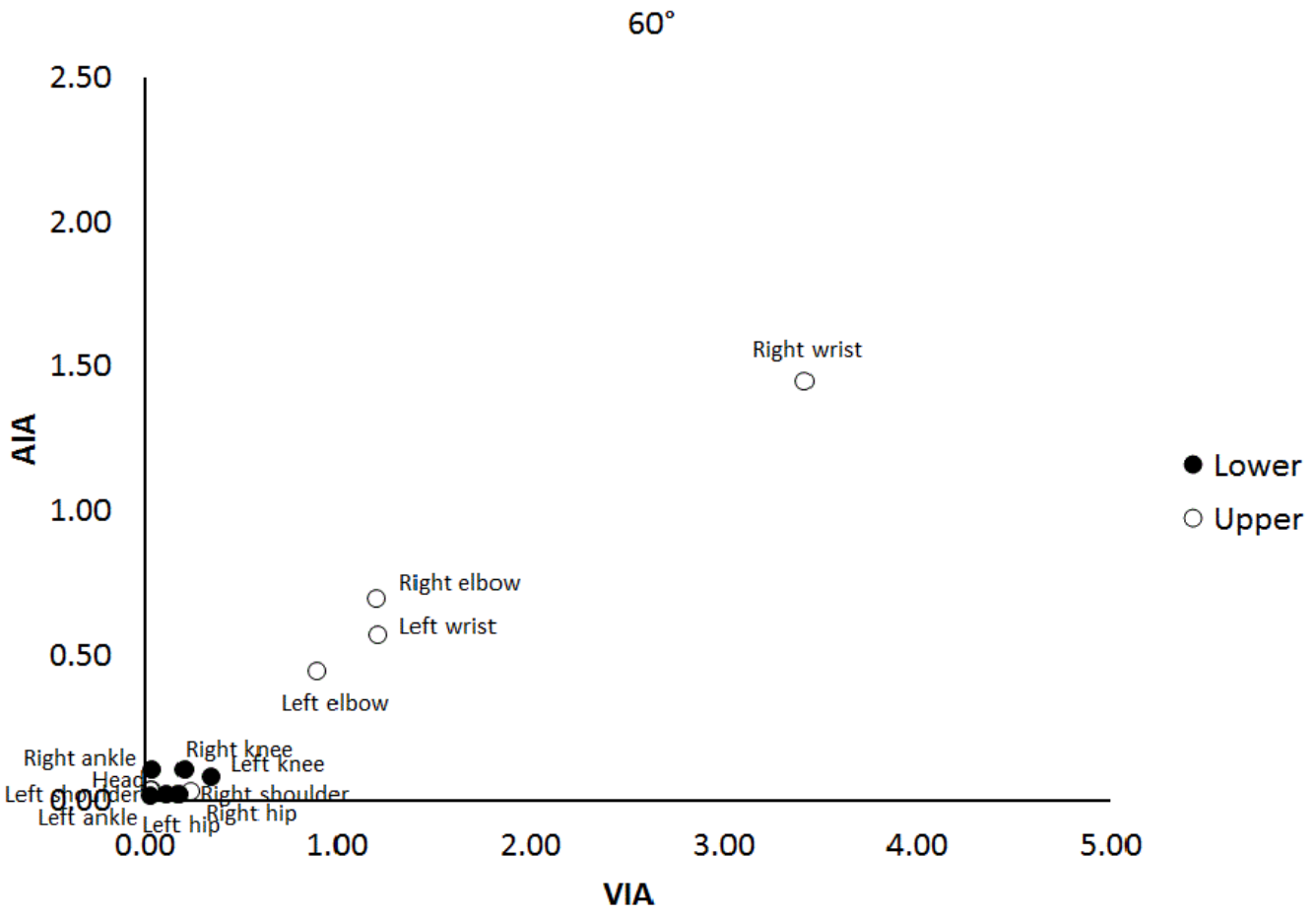

Figure 22. **Two-dimensional representations of VIA, AIA and $\widehat{\text{PPIA}}$ for each of the thirteen joints that comprise the animated hand walker stimulus (continued): 60° view.**

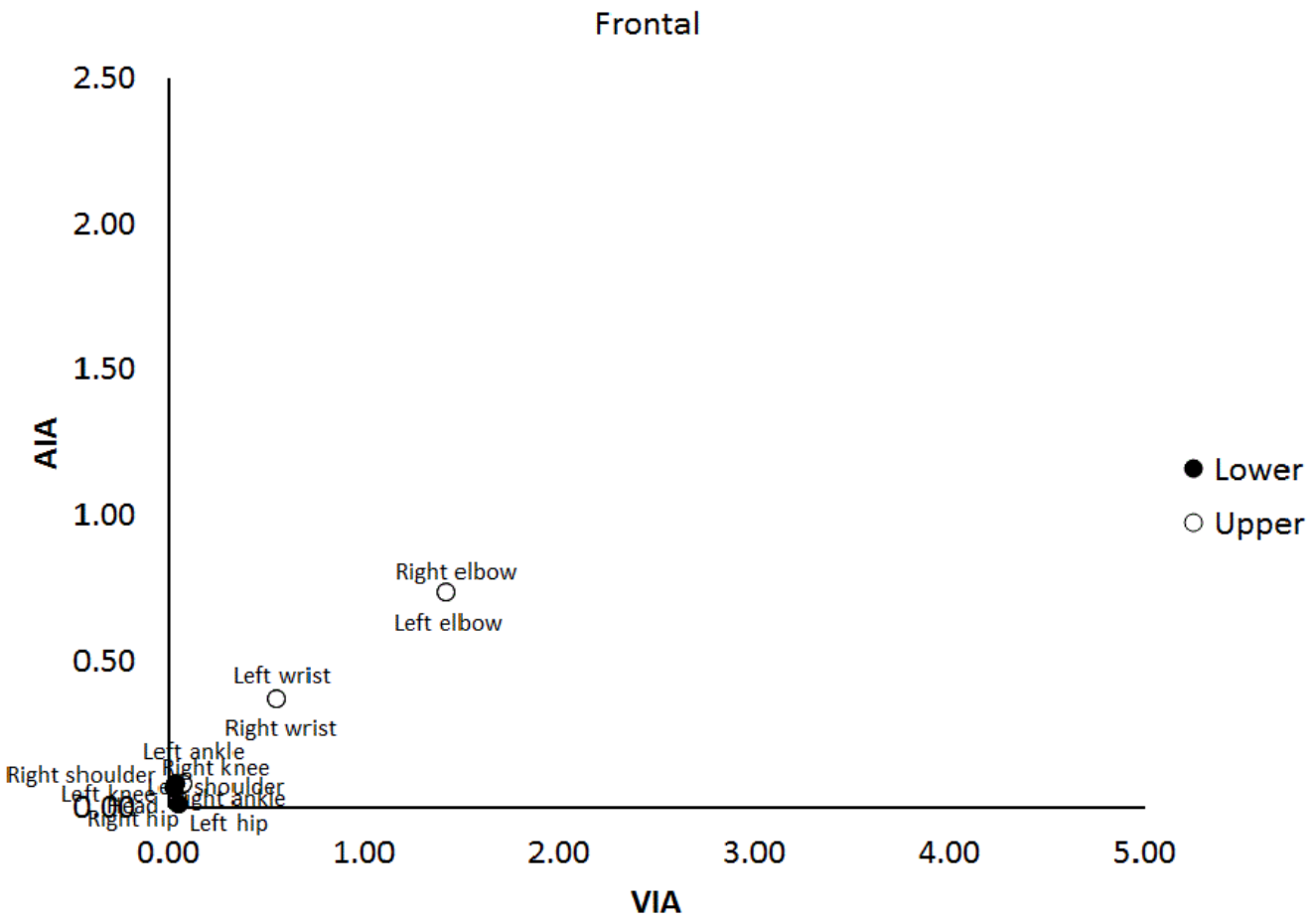

Figure 22. **Two-dimensional representations of VIA, AIA and $\widehat{\text{PPIA}}$ for each of the thirteen joints that comprise the animated hand walker stimulus (continued): frontal view.**

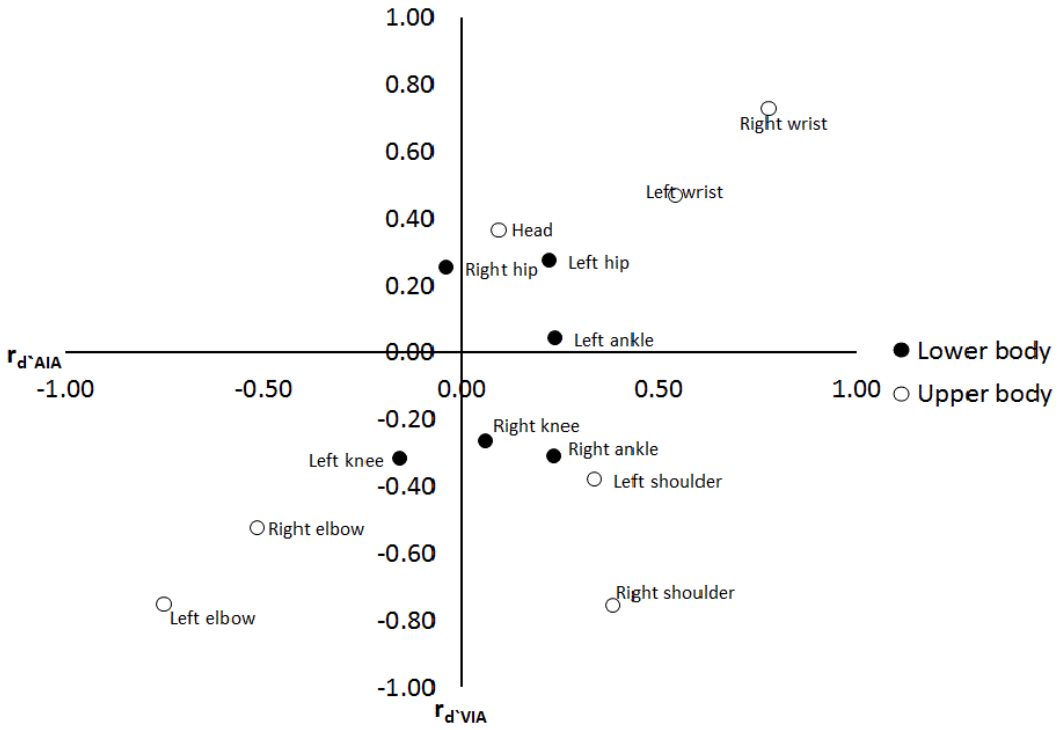

Figure 23. **Two-dimensional representations of correlations between VIA and sensitivity ($r_{d`VIA}$) and between AIA and sensitivity ($r_{d`AIA}$) for each of the thirteen joints that comprise the animated hand walker stimulus. The figure corresponds to the analysis of isolated presentations of body parts using multiple linear models including VIA or AIA.**

PHASE PORTRAIT ANALYSIS OF THE ANIMATED HUMAN ROWER

Figure 24 depicts the allocations on a two-dimensional orthogonal representation of the thirteen joints of the rowing animation correspondent to different orientations. In the case of this animation, wrists and elbows have VIA values greater than any other joint for profile, 30°, and 60° orientations. These results suggest that these joints carry more velocity information about the difference between forward and backward direction of motion than other joints.

Inspection of Figure 25 suggests the existence of distinctive patterns in the way the visual system uses kinematic information on asymmetry of the direction of articulated motion when analyzing different body parts of the rowing animation: More kinematic information is used for the analysis of the upper part and less for the lower part, even information from shoulders and head seems to have been used.

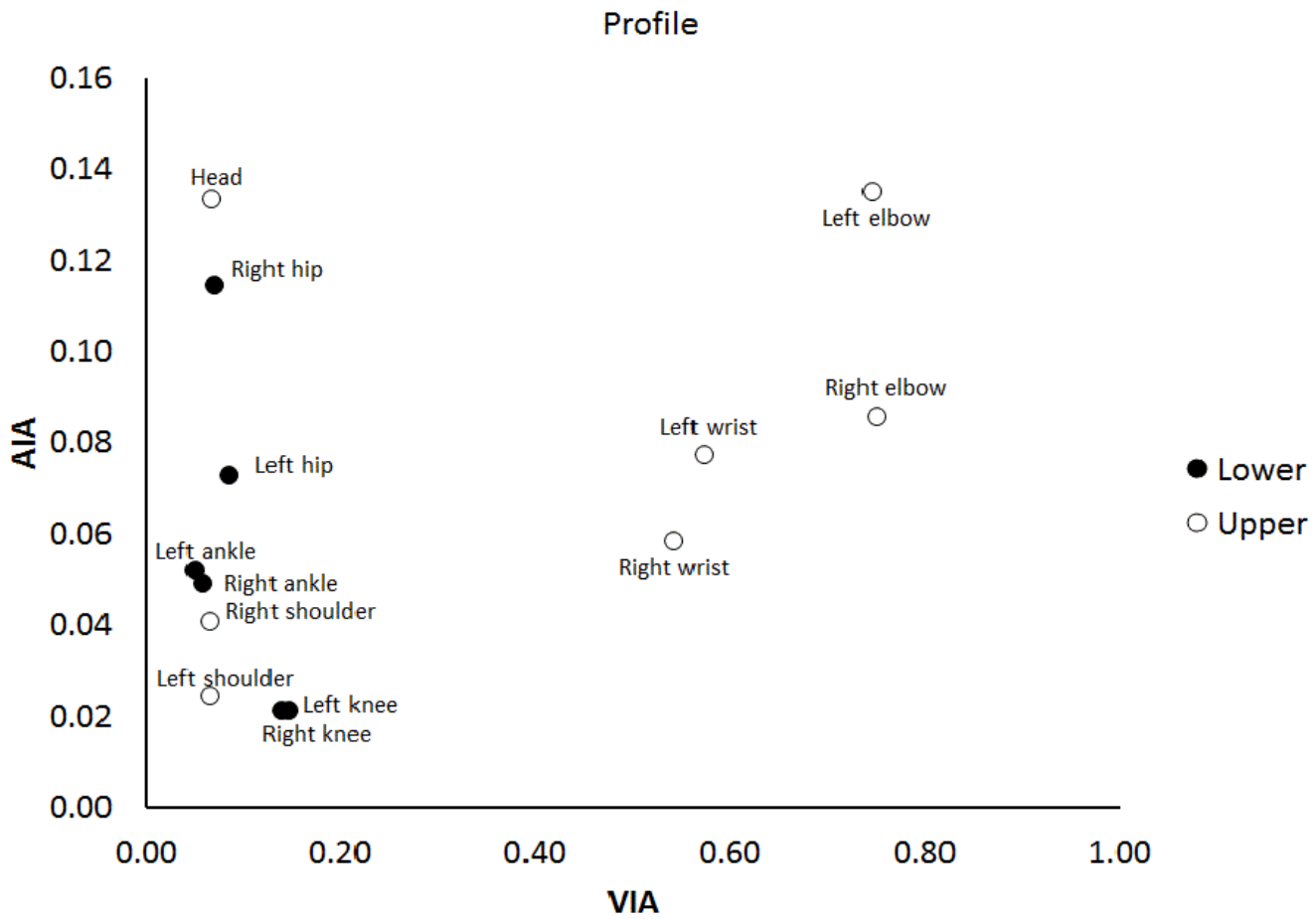

Figure 24. **Two-dimensional representations of VIA, AIA and $\widehat{\text{PPIA}}$ for each of the thirteen joints that comprise the animated rower stimulus: profile view.**

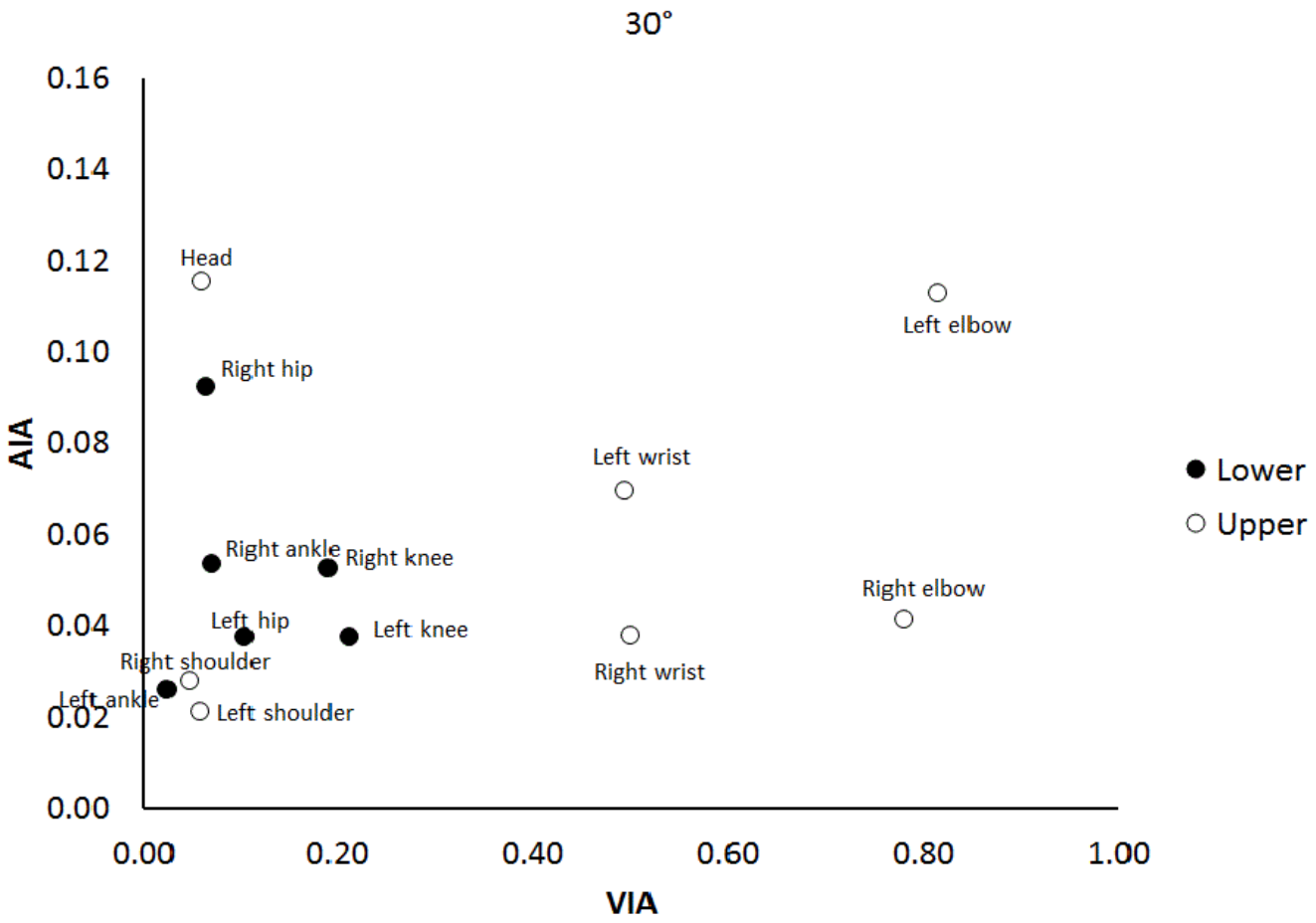

Figure 24. **Two-dimensional representations of VIA, AIA and $\widehat{\text{PPIA}}$ for each of the thirteen joints that comprise the animated rower stimulus (continued): 30° view.**

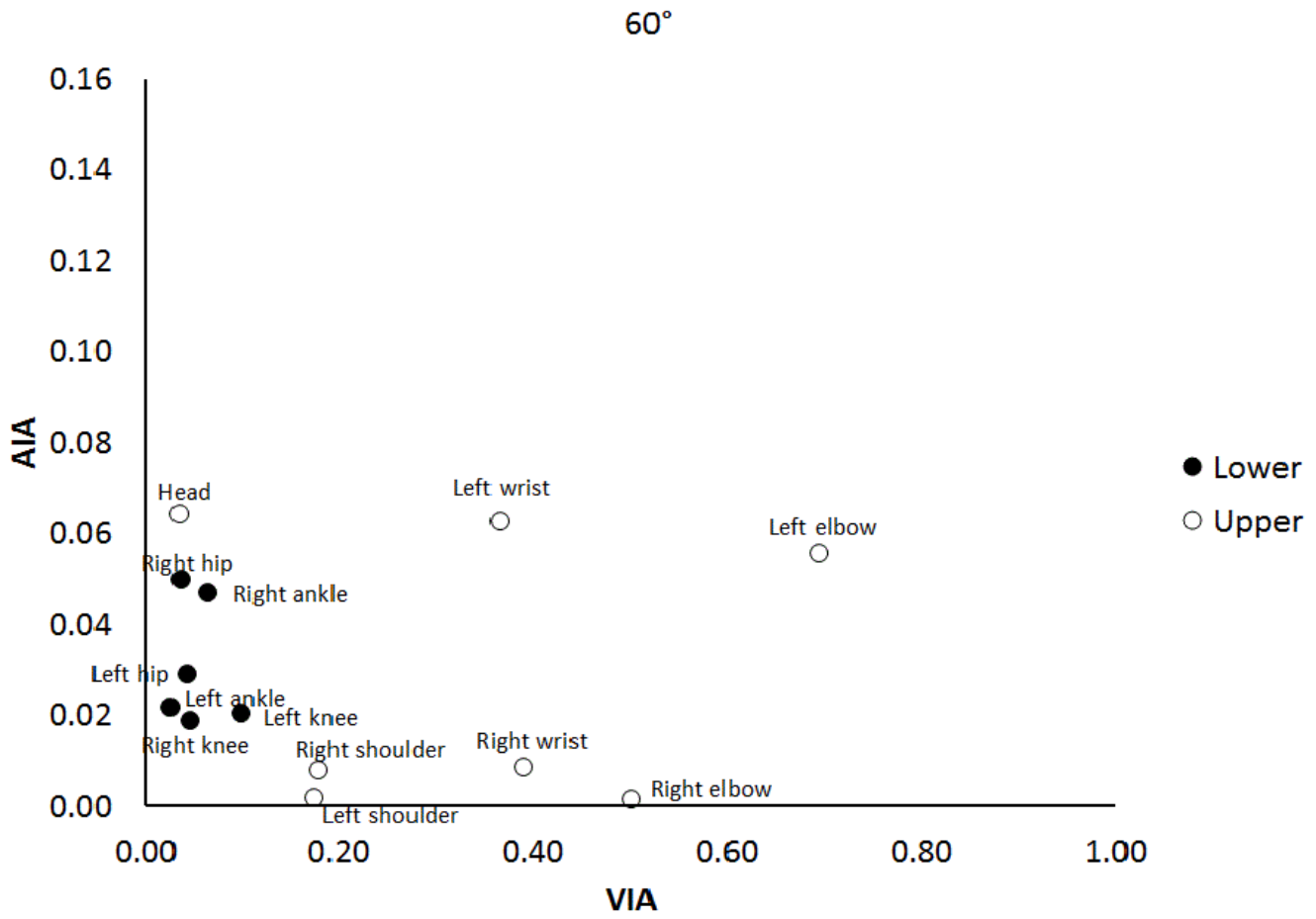

Figure 24. **Two-dimensional representations of VIA, AIA and $\widehat{\text{PPIA}}$ for each of the thirteen joints that comprise the animated rower stimulus (continued): 60° view.**

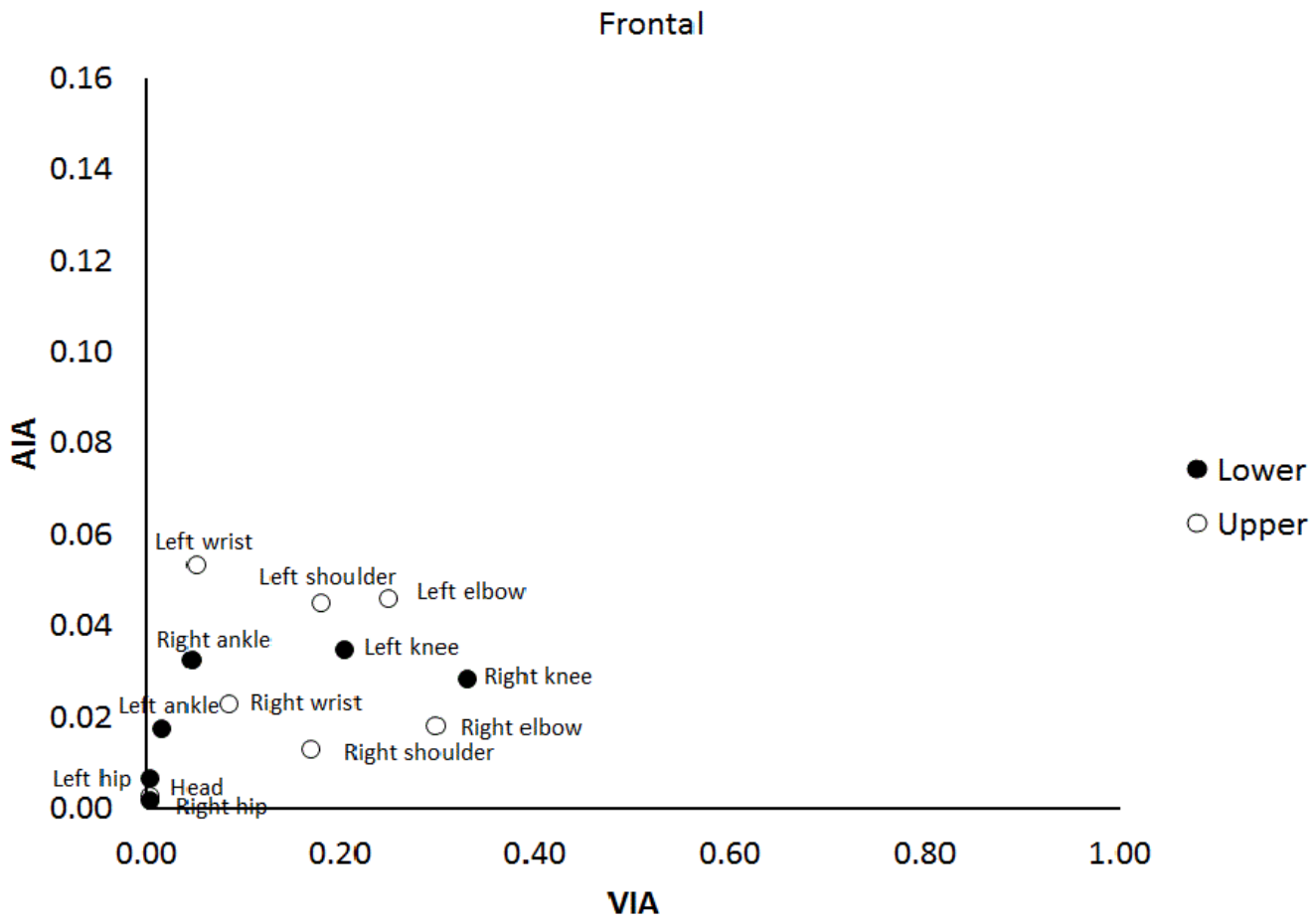

Figure 24. **Two-dimensional representations of VIA, AIA and $\widetilde{\text{PPIA}}$ for each of the thirteen joints that comprise the animated rower stimulus (continued): frontal view.**

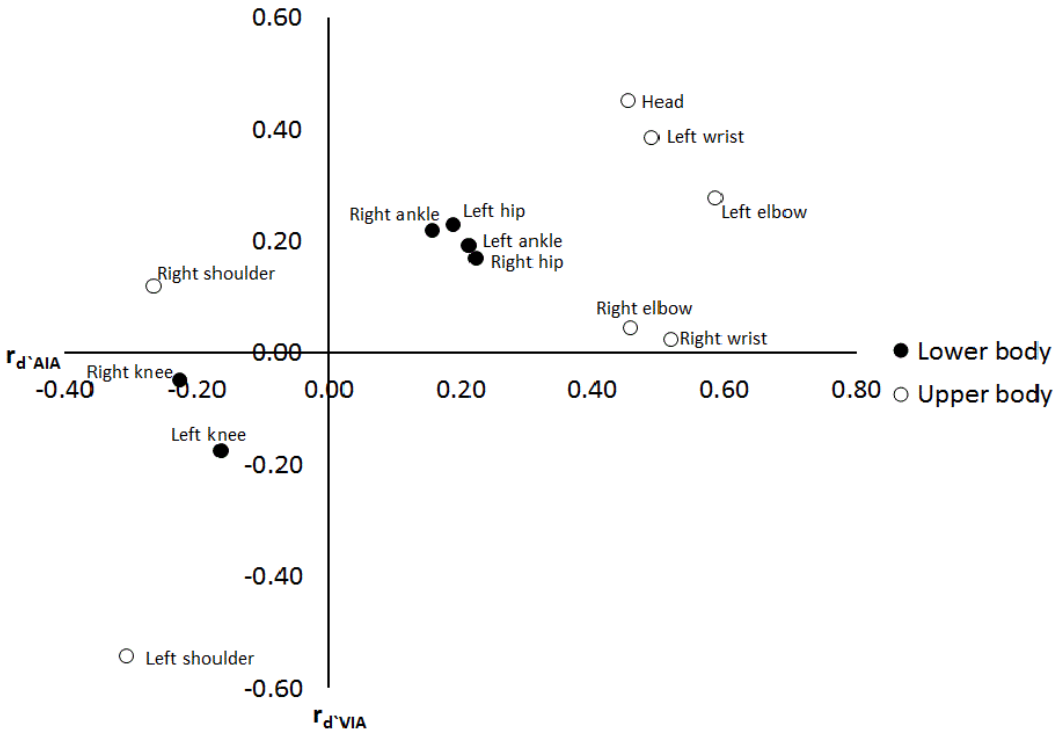

Figure 25. **Two-dimensional representations of correlations between VIA and sensitivity ($r_{d`VIA}$) and between AIA and sensitivity ($r_{d`AIA}$) for each of the thirteen joints that comprise the animated rower stimulus. The figure corresponds to the analysis of isolated presentations of body parts using multiple linear models including VIA or AIA.**

PHASE PORTRAIT ANALYSIS OF GROUP OF JOINTS

The phase portrait analysis using indexes and the phase portrait figure strictly speaking is only suitable for the analysis of the direction of motion of individual dots; the extension of the analysis to groups of dots has to be justified by stimulus and perceptual plausible considerations. For instance, if the analysis corresponds to the lower body of a point-light animation made of 13 points, the six points that conform the lower body may be naturally grouped because they correspond to a single stimulus when shown and biologically are representing a functional unit as well.

An additional issue related to the suitability of the phase portrait analysis for groups of dots is the selection of the mathematical or statistical procedure to make the grouping. In the case of a point-light still figure, a plausible selection would be the calculation of the center

of mass of the figure as the set of dots that conforms it, may be treated as a system of physical particles and apply standard techniques for its calculation (Zatsiorsky, 2002, p. 269). Moreover, the individual "masses" for the dots may be taken as constants with the same value and after straightforward calculations, the center of mass of the figure would reduce to the averaged position of the dots under analysis. Similar considerations for the case of a moving figure can be taken into account to calculate the average velocity or acceleration of the dots under analysis and use them as the group velocity or acceleration.

As the computing of correlations for repeated measures data using the techniques developed by Bland and Altman (1995) requires numerical results calculated with the multiple linear model and ANOVA, we should take into account the problem of multicollinearity among VIA, AIA, and PPIA correspondent to several joints. In the case of multiple linear models using several potential predictive values, the quantification of the contribution of each individual kinematic regressor to the explanation of the total variance was a simple task as long as the included regressors were uncorrelated: a single kinematic index plus thirteen dummy variables. As VIA, AIA, and PPIA are correlated, the task is not simple anymore when using models including at least two of these three indexes. To quantify their relative importance using ANOVA, we can apply a procedure available in R version 3.0.2 (2013-09-25) to average sequential sums of squares over orderings of regressors. This technique has been proposed by Lindeman, Merenda and Gold (as cited in Grömping, 2006) being known as the LMG method.

We applied the above mentioned considerations to calculate asymmetries among group velocities and accelerations correspondent to forward and backward motion using phase portrait indexes. Table 9 depicts averages and standard deviations of VIA, AIA, $\widetilde{\text{PPIA}}$ and PPIA correspondent to the upper and lower body joints for each of the four actions analyzed in this chapter. A quick inspection of the four phase portrait parameters, suggests first that in averages and standard deviations, $\widetilde{\text{PPIA}}$ and PPIA have similar values. Second, in averages and standard deviations, VIA values are higher than AIA's. However, at the level of individual joints as it was shown in Figures 18, 20, 22, and 24 VIA values are higher than AIA's for some joints and AIA values are higher than VIA´s for others. Third, the averaged kinematic information is consistent with the performance in experiments when analyzing them for isolated body parts. In the case of the walking animation indexes are higher for the

lower part than for the upper while in the case of the hand walking animation indexes are higher for the upper part than for the lower. The differences among upper and lower indexes for the rowing animation, resemble the pattern found for the hand walker but less pronounced. Finally, the crawling animation shows differentiated kinematic patterns for specific orientations: Upper indexes are higher than lower's for profile orientation and the other way around for most of the indexes in other orientations.

Table 9

Averaged phase portrait indexes correspondent to upper or lower body for profile, 30°, 60°, and frontal orientations of animations used in Chapter 3.

	Walker					Crawler			
	$\overline{\text{VIA}}$	$\overline{\text{AIA}}$	$\overline{\overline{\text{PPIA}}}$	$\overline{\text{PPIA}}$		$\overline{\text{VIA}}$	$\overline{\text{AIA}}$	$\overline{\overline{\text{PPIA}}}$	$\overline{\text{PPIA}}$
Upper 0°	0.49 (0.46)	0.18 (0.11)	0.53 (0.46)	0.55 (0.49)	Upper 0°	0.65 (0.55)	0.19 (0.13)	0.68 (0.55)	0.70 (0.59)
Lower 0°	0.90 (1.34)	0.33 (0.49)	0.97 (1.43)	0.94 (1.40)	Lower 0°	0.55 (0.41)	0.13 (0.10)	0.57 (0.42)	0.59 (0.44)
Upper 30°	0.46 (0.41)	0.15 (0.09)	0.49 (0.41)	0.51 (0.43)	Upper 30°	0.47 (0.36)	0.13 (0.11)	0.49 (0.37)	0.50 (0.40)
Lower 30°	0.70 (0.97)	0.35 (0.52)	0.81 (1.08)	0.81 (1.10)	Lower 30°	0.53 (0.40)	0.11 (0.08)	0.54 (0.40)	0.56 (0.42)
Upper 60°	0.27 (0.22)	0.10 (0.06)	0.29 (0.23)	0.30 (0.23)	Upper 60°	0.16 (0.12)	0.07 (0.05)	0.19 (0.11)	0.19 (0.13)
Lower 60°	0.49 (0.65)	0.24 (0.29)	0.55 (0.71)	0.53 (0.70)	Lower 60°	0.34 (0.27)	0.07 (0.06)	0.35 (0.27)	0.36 (0.28)
Upper 90°	0.04 (0.02)	0.03 (0.02)	0.05 (0.02)	0.03 (0.02)	Upper 90°	0.17 (0.17)	0.07 (0.08)	0.18 (0.19)	0.19 (0.20)
Lower 90°	0.14 (0.14)	0.12 (0.09)	0.20 (0.15)	0.21 (0.17)	Lower 90°	0.24 (0.21)	0.05 (0.06)	0.25 (0.22)	0.26 (0.23)

We may use the VIA and AIA averaged indexes shown in Table 9, to calculate correlations between performance and kinematic properties of body parts. As we did before,

we may derive these correlations from multiple linear models but now including VIA and AIA as regressors. The models we are about to introduce use the contributions of all dots that belong to a specific body part, but merged as averages.

Table 9

Averaged phase portrait indexes correspondent to upper or lower body for profile, 30°, 60°, and frontal orientations of animations used in Chapter 3 (continued).

	Hand walker					Rower			
	$\overline{\text{VIA}}$	$\overline{\text{AIA}}$	$\overline{\overline{\text{PPIA}}}$	$\overline{\text{PPIA}}$		$\overline{\text{VIA}}$	$\overline{\text{AIA}}$	$\overline{\overline{\text{PPIA}}}$	$\overline{\text{PPIA}}$
Upper 0°	1.30 (1.52)	0.74 (0.92)	1.51 (1.77)	1.59 (1.90)	Upper 0°	0.40 (0.32)	0.08 (0.04)	0.42 (0.31)	0.42 (0.32)
Lower 0°	0.14 (0.01)	0.05 (0.04)	0.15 (0.03)	0.12 (0.03)	Lower 0°	0.09 (0.04)	0.05 (0.04)	0.11 (0.03)	0.09 (0.04)
Upper 30°	1.30 (1.57)	0.67 (0.78)	1.47 (1.75)	1.53 (1.84)	Upper 30°	0.39 (0.34)	0.06 (0.04)	0.41 (0.33)	0.40 (0.33)
Lower 30°	0.09 (0.07)	0.04 (0.02)	0.10 (0.07)	0.07 (0.08)	Lower 3 0°	0.11 (0.07)	0.05 (0.02)	0.13 (0.07)	0.12 (0.08)
Upper 60°	1.01 (1.18)	0.46 (0.51)	1.11 (1.28)	1.14 (1.32)	Upper 60°	0.34 (0.22)	0.03 (0.03)	0.06 (0.02)	0.06 (0.03)
Lower 60°	0.16 (0.12)	0.06 (0.04)	0.17 (0.11)	0.17 (0.13)	Lower 60°	0.05 (0.03)	0.03 (0.01)	0.06 (0.02)	0.06 (0.03)
Upper 90°	0.60 (0.61)	0.34 (0.30)	0.69 (0.68)	0.72 (0.74)	Upper 90°	0.15 (0.11)	0.03 (0.02)	0.15 (0.10)	0.15 (0.10)
Lower 90°	0.04 (0.01)	0.05 (0.04)	0.07 (0.02)	0.05 (0.02)	Lower 90°	0.10 (0.14)	0.02 (0.01)	0.11 (0.13)	0.11 (0.13)

Table 10 depicts the results of the analysis of performance for each animation shown as upper or lower body, portraying the importance (amount of explained variance) of each kinematic regressor: $\overline{VIA}$ and $\overline{AIA}$, and the importance of each of the 13 dummy variables with which we include within the models the contributions to performance from subjects (14 different subjects for each animation) who participated in the experiments.

Table 10

Importance of explanatory models of performance in experiments of Chapter 3 using half body animations. Importance is calculated by the LMG method. Performance corresponds to results reported in Chapter 3.

	Walker		Crawler		Hand walker		Rower	
Regressor	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower
$\overline{\text{VIA}}$	0.018	0.124	0.111	0.396	0.353	0.006	0.201	0.010
$\overline{\text{AIA}}$	0.014	0.152	0.104	0.286	0.204	0.047	0.040	0.028
Dummy1	0.155	0.006	0.004	0.007	0.002	0.004	0.002	0.004
Dummy2	0.004	0.006	0.001	0.008	0.003	0.046	0.002	0.011
Dummy3	0.005	0.006	0.020	0.001	0.001	0.018	0.002	0.003
Dummy4	0.020	0.012	0.006	0.000	0.002	0.033	0.087	0.114
Dummy5	0.052	0.006	0.032	0.000	0.001	0.036	0.151	0.004
Dummy6	0.004	0.004	0.002	0.003	0.002	0.011	0.004	0.007
Dummy7	0.009	0.006	0.004	0.000	0.027	0.144	0.011	0.143
Dummy8	0.020	0.007	0.002	0.002	0.012	0.008	0.009	0.008
Dummy9	0.005	0.025	0.001	0.012	0.002	0.017	0.005	0.003
Dummy10	0.026	0.002	0.014	0.001	0.004	0.014	0.005	0.005
Dummy11	0.076	0.006	0.031	0.006	0.021	0.029	0.041	0.005
Dummy12	0.004	0.032	0.020	0.004	0.001	0.062	0.006	0.003
Dummy13	0.029	0.073	0.018	0.008	0.003	0.061	0.041	0.129
R^2	0.441	0.467	0.370	0.734	0.638	0.536	0.607	0.477

In the case of the upper walker, 44.1% of total variance in performance is explained by its correspondent model and 3.2% by the kinematic regressors. In the case of the lower walker, 46.7% of total variance is explained by its correspondent model and 27.6% by the kinematic regressors: There is a larger contribution of lower kinematics to explain performance in comparison to upper kinematics.

For the upper and lower crawlers we have 37.0% and 73.4% of total variance explained by the models with 21.5% and 68.2% explained within each model by the kinematic regressors: There is a larger contribution of the lower kinematics in comparison to the upper kinematics.

In the case of the upper hand walker, we found for the upper part, 63.8% of total variance explained by its correspondent model and for the lower part 53.6%. Within each model, 55.7% is explained by kinematic regressors for the upper part and 5.3% for the lower part. A similar pattern becomes apparent for the rower but less pronounced: 60.7% of total variance explained by the correspondent model for the upper part and 47.7% by the correspondent model for the lower part. Within each model, 24.1% is explained by kinematic regressors for the upper part and 3.8% for the lower part: There are larger contributions of upper kinematics compared to lower kinematics.

We have been able to estimate the importance of VIA and AIA indexes for each body part. Table 11 compares the amount of total explained variance by the already discussed models including $\overline{\text{VIA}}$ and $\overline{AIA}$ and new multiple linear models including $\overline{PPIA}$ instead of $\overline{VIA}$ and $\overline{AIA}$'s. Explanatory importance is higher in the models that include $\overline{VIA}$ and $\overline{AIA}$ when compared with explanatory importance of the models that include $\overline{PPIA}$ with the exception of the upper crawler model where they are almost equal. In all the models that use $\overline{PPIA}$, there were differences between the total amount of explained variance by upper and lower parts, these differences were as expected: Lower part is more informative for the walker and upper part is more informative for the hand walker and rower. In the case of the crawler, the lower part seems to be more informative than the upper but the upper part would be informative enough.

Table 11

Importance of explanatory models of performance in experiments of Chapter 3 using half body animations. Importance is calculated by the LMG method using as regressors $\overline{VIA}$ and $\overline{AIA}$, or using $\overline{PPIA}$. Performance corresponds to results reported in Chapter 3.

	Walker		Crawler		Hand walker		Rower	
Regressor	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower
$\overline{\text{VIA}}$; $\overline{\text{AIA}}$	0.032	0.276	0.215	0.682	0.557	0.053	0.242	0.038
$\overline{\text{PPIA}}$	0.023	0.247	0.217	0.505	0.416	0.001	0.179	0.008

Table 12 shows $r_{d'VIA,}$ $r_{d'AIA}$ and $r_{d'PPIA}$ for each upper and lower body model. Magnitudes of these correlations follow the expected trend, being one of the two body parts more informative than the other.

Table 12

Correlations between performance in experiments of Chapter 3 using half body animations and $\overline{VIA}$, $\overline{AIA}$, or $\overline{PPIA}$. Importance is calculated by the LMG method. Performance corresponds to results reported in Chapter 3.

	Walker		Crawler		Hand walker		Rower	
Regressor	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower
$r_{d'\overline{VIA}}$	0.175	0.434	0.387	0.773***	0.702***	0.109	0.582***	-0.138
$r_{d'\overline{AIA}}$	-0.156	0.472	-0.376	-0.719***	-0.600**	-0.304*	-0.301*	0.228
$r_{d'\overline{PPIA}}$	0.199	0.553***	0.507***	0.730***	0.673***	-0.050	0.531***	-0.118

*p<.05. **p<.01. ***p<.001.

Tables 13 and 14 compare across models the importance (total amount of explained variance) using VIA and AIA regressors. Lower and upper correspond to information already discussed in Tables 10 and 11 but it is included here for comparison purposes, with models using as regressors VIA and AIA of specific joints. In the case of the walker, left knee regressors explain 34.9% of the variance while lower regressors explain 27.6%, the right wrist regressors and the upper regressors explain the same amount: 3.2%. For the crawler, right ankle regressors explain 81.6% and lower regressors 68.2%, left elbow regressors explain 52.9% and upper regressors 21.5%. Performance for upper hand walker is explained by left elbow or right shoulder regressors with 56.6%, and for lower hand walker by right ankle regressors with 5.7% and by lower regressors by 5.3%. In the case of the upper rower, left wrist regressors explain 24.7 % and upper regressors 24.2%, while for the lower rower, left ankle regressors explain 3.3% and lower regressors 3.8%. In general, the amount of explanation given by regressors correspondent to specific joints, equals or is greater than the

amount of explanation given by regressors correspondent to averaged kinematic information from groups of joints.

Table 13

Importance and correlations of explanatory models of performance in Experiments 2 and 3 of Chapter 3 calculated by the LMG method. VIA and AIA are used as regressors. LW: Left wrist. LE: Left elbow. LS: Left shoulder. RW: Right wrist. RE: Right elbow. RS: Right shoulder. LA: Left ankle. LK: Left knee. LH: Left hip. RA: Right ankle. RK: Right knee. RH: Right hip.

	Walker			Crawler		
Regressor	Importance	$r_{d'VIA}$	$r_{d'AIA}$	Importance	$r_{d'VIA}$	$r_{d'AIA}$
Lower	0.276	0.434	0.472	0.682	0.773***	-0.719***
LA	0.318	0.509*	-0.480	0.488	0.649***	-0.501***
LK	0.349	-0.580**	0.451	0.413	0.527	0.528
LH	0.156	0.333	-0.319	0.260	0.447*	-0.337
RA	0.284	0.424	0.494*	0.816	0.887***	-0.828***
RK	0.268	0.203	-0.593***	0.738	0.801	0.795
RH	0.317	-0.268	0.602***	0.807	-0.876***	-0.842
Upper	0.032	0.175	-0.156	0.215	0.387	-0.376
H	0.009	0.065	0.107	0.154	0.110	0.417**
LW	0.023	0.144	-0.140	0.322	0.487	0.482
LE	0.026	0.166	-0.133	0.529	-0.628***	0.711***
LS	0.028	0.140	-0.168	0.486	0.382***	0.736***
RW	0.032	0.175	-0.161	0.360	0.181	0.192
RE	0.029	0.173	-0.143	0.167	0.364	-0.291
RS	0.029	0.145	0.172	0.102	0.326*	0.136

*p<.05. **p<.01. ***p<.001.

Tables 13 and 14 show also the Pearson correlations for the different analyzed models. In general, a greater importance implies higher magnitude and significance of the correspondent correlation.

Table 14

Importance and correlations of explanatory models of performance in Experiments 4 and 5 of Chapter 3 calculated by the LMG method. VIA and AIA are used as regressors. LW: Left wrist. LE: Left elbow. LS: Left shoulder. RW: Right wrist. RE: Right elbow. RS: Right shoulder. LA: Left ankle. LK: Left knee. LH: Left hip. RA: Right ankle. RK: Right knee. RH: Right hip.

	Hand walker			Rower		
Regressor	Importance	$r_{d'VIA}$	$r_{d'AIA}$	Importance	$r_{d'VIA}$	$r_{d'AIA}$
Lower	0.053	0.109	-0.304*	0.038	-0.138	0.228
LA	0.033	0.245	0.067	0.033	0.187	-0.160
LK	0.053	-0.115	-0.302	0.018	0.116	-0.138
LH	0.039	0.164	0.226	0.030	0.138	0.187
RA	0.057	0.194	-0.281	0.032	-0.134	0.202
RK	0.054	0.142	-0.295*	0.028	-0.251	0.046
RH	0.046	-0.122	0.278	0.029	-0.162	0.164
Upper	0.557	0.702***	-0.600***	0.242	0.582***	-0.301*
H	0.227	-0.276*	0.445***	0.239	0.486**	-0.480**
LW	0.439	0.590***	-0.526***	0.247	0.533***	-0.442**
LE	0.566	-0.665*	-0.669*	0.246	0.591***	-0.299
LS	0.231	0.358*	-0.398	0.235	-0.343*	-0.560***
RW	0.561	0.685**	-0.636	0.240	0.586***	-0.284*
RE	0.291	-0.426	-0.440	0.226	0.553***	-0.323**
RS	0.566	-0.446*	-0.759***	0.087	-0.317*	-0.212

*p<.05. **p<.01. ***p<.001.

Table 15 compares across models the importance (total amount of explained variance) using PPIA regressors. Lower and upper correspond to information already discussed in Tables 10 and 11 but it is included here for comparison purposes, with models using as regressors PPIA of specific joints.

Table 15

Importance and correlations of explanatory models of performance in experiments of Chapter 3 calculated by the LMG method. PPIA is used as a regressor. LW: Left wrist. LE: Left elbow. LS: Left shoulder. RW: Right wrist. RE: Right elbow. RS: Right shoulder. LA: Left ankle. LK: Left knee. LH: Left hip. RA: Right ankle. RK: Right knee. RH: Right hip. I: Importance.

	Walker		Crawler		Hand walker		Rower	
Regressor	Importance	$r_{d'PPIA}$	Importance	$r_{d'PPIA}$	Importance	$r_{d'PPIA}$	Importance	$r_{d'PPIA}$
Lower	0.247	0.553***	0.505	0.730***	0.001	-0.050	0.008	-0.118
LA	0.260	0.568***	0.159	0.713**	0.010	0.140	0.021	0.196
LK	0.346	-0.654***	0.449	0.688***	0.022	-0.207	0.020	-0.186
LH	0.052	0.254	0.246	0.509***	0.014	0.165	0.018	0.178
RA	0.250	0.556***	0.651	0.829***	0.033	0.252	0.022	0.200
RK	0.090	-0.334*	0.734	0.880***	0.002	-0.066	0.028	-0.226
RH	0.156	0.439**	0.815	-0.927***	0.001	-0.049	0.030	0.230
Upper	0.023	0.199	0.217	0.507***	0.416	0.673***	0.179	0.531***
H	0.018	0.172	0.000	-0.018	0.229	0.499***	0.128	0.450**
LW	0.023	0.196	0.327	0.622***	0.252	0.524 ***	0.161	0.504***
LE	0.024	0.201	0.327	0.622***	0.531	-0.760 ***	0.212	0.579***
LS	0.000	0.013	0.008	0.095	0.078	0.292	0.084	-0.364
RW	0.022	0.192	0.028	0.181	0.546	0.771 ***	0.168	0.516***
RE	0.027	0.214	0.144	0.412**	0.317	-0.587 ***	0.124	0.443**
RS	0.030	0.226	0.101	0.346*	0.058	0.429	0.053	-0.289

*p<.05. **p<.01. ***p<.001.

In the case of the walker, left knee PPIA explains 34.6% of the variance while lower PPIA explains 24.7%, the right shoulder PPIA explains 3% and upper PPIA 2.3%. For the crawler, right hip PPIA explains 81.5% and lower PPIA 50.5%, left elbow and left wrist PPIAs explain the same: 32.7% and upper PPIA 21.7%. Performance for upper hand walker is explained by right wrist PPIA with 54.6% and by upper PPIA with 41.6%, and for lower hand walker, by right ankle PPIA with 3.3% and by lower PPIA by 0.1%. In the case of the

upper rower, left elbow PPIA explains 21.2% and upper PPIA 17.9%, while for the lower rower, right hip PPIA explains 3% while lower PPIA 0.8%. In general, the amount of explanation given by PPIA correspondent to specific joints, is greater than the amount of explanation given by PPIA correspondent to averaged kinematic information from groups of joints. Table 15 shows also the Pearson correlations for the different analyzed models. Again, a greater importance implies higher magnitude and significance of the correspondent correlation.

DISCUSSION

In previous chapters we have shown differences in sensitivity between the lower part and the upper part or between the frontal and non-frontal orientations of a point-light walker when the task of the observer is to judge the direction of articulation of the animation. We hypothesized that differences in sensitivity are related to asymmetries in the motions of the dots that constitute each stimulus. The goal of the present chapter was to introduce a technique to visualize and estimate information on asymmetry in velocity and accelerations of the dots. More specifically, we introduced novel kinematic indexes (VIA, AIA, $\widetilde{PPIA}$ and PPIA) and a phase portrait representation that provide information on the size of asymmetries in either velocity, or acceleration or both. To demonstrate the applicability of the technique we illustrated how these indexes can be employed to explain measures on sensitivity (d') using Pearson correlations and estimation of their importance.

In experiments of Chapter 3, body part (upper, lower, and full) and orientation (profile, 30°, 60°, and frontal) were the explanatory variables of results. In order to link the analysis of these results to the PP technique, we needed to summarize the kinematic information of individual joints by body parts and orientations: For each action there were three data sets of 56 observations of performance correspondent to 14 participants (four observations for each observer for profile, 30°, 60°, and frontal orientations). Two of the data sets contained responses to isolated body parts (upper or lower) while the third one contained responses to full body animations. In the following paragraphs we proceed to discuss the procedures we have applied and discuss their utility and limits.

What follows are the findings for the analysis of the four animations. First, by depiction of VIA and AIA on two-dimensional planes, it is possible to visualize the amount

of information about velocity and acceleration carried by each body joint. As expected, the walker carries more kinematic information in the lower part than in the upper while the hand walker and rower carry more kinematic information in the upper part. The crawler may be considered as an "in between" case carrying enough kinematic information in both body parts. Second, it is possible to visualize with two-dimensional representations, differences across orientations. As expected, the animations carry less kinematic information in the frontal orientation. Third, using two-dimensional representations of correlations between sensitivity and VIA and between sensitivity and AIA, it is possible to analyze the performance explained by kinematic information carried by upper and lower joints and compare by visualization these explanations. Fourth, using multiple linear analysis, ANOVA and the LMG method, it is possible to quantify and compare the importance of single joints when their indexes VIA and AIA or PPIA are introduced as regressors to explain performance. Five, using multiple linear analysis, ANOVA, the LMG method and averaged kinematic information from body parts using $\overline{VIA}$ and $\overline{AIA}$, it is possible to quantify the importance of body parts to explain performance.

Using the PP techniques, we have analyzed performance for isolated body parts and reported it but not for full-body. For the sake of conciseness, we have omitted the presentation of results of the analysis for full body presentations as it did not show any differentiated pattern based on kinematic properties of body parts or their joints as it has happened with isolated body parts. Apparently, isolated presentation strengthen the coupling of kinematic information with performance in comparison to the couplings that take place in non-isolated presentations.

Using multiple linear models, ANOVA, and the LMG method, we have been able to estimate the importance (amount of explained variance), the magnitude, the sign and provide the significance of Pearson correlations between sensitivity and AIA, VIA or PPIA. Because of the characteristics of our data (with correlated regressors and kinematic indexes only available for four orientations), we were not able to introduce more than two kinematic regressors in each multiple linear model. In principle, it would be possible to stretch the analysis we have done to include two regressors correspondent to different joints but reasonable theoretical considerations would be needed to choose them.

The VIA, AIA, and PPIA indices are appropriate tools to quantify the asymmetry of the direction of motion both at the level of individual joints and at the level of groups of them as we have done in the previous analysis. But other stimulus manipulations are possible too. Pollick, Fidiopiastis, and Braden (2001), for instance, developed a technique to exaggerate tennis serves in solid body animations. In our case, it could be interesting to diminish the asymmetry present in the lower part of the walker and see if performance drops or to exaggerate asymmetry in the upper part of the walker and see if performance increases.

The indexes, as they were introduced here, are computed on horizontal motions only. We believe that for the purpose of the present chapter, asymmetries in horizontal motions were crucial and most informative. This does not mean, however, that the computation of the indexes should always be restricted to asymmetries in the horizontal dimension. For other purposes, for example, asymmetries in the vertical direction might be more diagnostic. Indeed, recent studies (Chang & Troje, 2008, 2009a, 2009b; Saunders et al., 2009; Troje & Westhoff, 2006) suggest the existence of a 'life detector': A visual filter that is tuned to quickly and automatically detect the presence of a moving living organism and direct attention to it. The mechanism is found to be specifically sensitive to the gravitational forces on the legs and to acceleration in the motion. The filter is believed to be evolutionarily old and innate, and its main function would be to alert the observer to a potentially dangerous or otherwise demanding situation (Troje & Chang, 2013). Computing the indexes introduced in the present chapter, but on the vertical dimension and relating these indexes to performance on detection tasks could advance research on the 'life detector'. Note also, that it is possible in principle to create indexes that detect asymmetries in motions combining the information provided by horizontal and vertical movements; if Cartesian coordinates are transformed to polar coordinates, the radius vector and the angle will carry horizontal and vertical kinematic information of interest.

Chapter 5

Perception of the direction of articulation of motion of animations derived from a single walker data

ABSTRACT

The purpose of the present study is to compare perception of forward and backward point-light walkers versus their reversed displays. On each trial, participants were presented with an upper, lower or full forward/backward moving walker (signal) or their reversed versions (noise) and they had to decide on the direction of their movements. We analyzed sensitivity (d') measures derived from response to signal and noise stimuli as well as response bias (c). We did not find any statistically significant effect on the sensitivity of the direction of original articulation (forward vs. backward) and found statistically significant effects of body parts (upper, lower or full). We did find statistically significant effects on bias of the direction of original articulation, body parts and the interaction.

INTRODUCTION

As we have already discussed before (see Chapter 2), we failed to observe a statistically significant effect of direction of articulation on the detection of a point-light walker in a simultaneous-masking paradigm. We were not able to find significant differences between detection of forward versus scrambled forward and detection of backward versus scrambled backward full walkers using a simultaneous masking paradigm. Additionally, we reported in Chapter 3 (revisit Experiments 1 and 2) that sensitivity d' measurements comparing forward versus backward walking were higher for full and lower bodies than for upper body.

The primary aim of the present study is to compare perception of forward and backward point-light walkers built from original forward and backward walking versus their reversed displays. In previous chapters, we created backward walkers by reversed display of forward animations that had been generated from original forward motion walking (see Dekeyser et al., 2002 and Vanrie & Verfaillie, 2004). There are several motivations that drove our decision of using original backward walking in the experimentation reported in this chapter: 1) In the biological motion perception literature, implementation of backward

walking point-light displays has been reported as reversed displays of forward walking as if it were on a treadmill (see for instance Verfaillie, 2000; Kuhlmann et al., 2009): We are not aware of the existence of studies using original backward point-light displays, 2) Viviani, Figliozzi, Campione, and Lacquaniti (2011) reported above chance level probabilities of correct response towards original forward walking and reversed backward walking video displays of the lower body part and reduced but just above chance level probabilities of correct response towards original backward walking and reversed forward walking. These results suggest that forward walking is easier to detect irrespective of being original forward motion or not. As studies exploring the contribution of body parts using point-light displays of original backward walking have not been reported yet, it would be of interest to widen the available empirical evidence, 3) Clinical studies of backward walking have taken place for treatment of Parkinson's disease by using translational backward walking routines (Hackney and Earhart, 2009) and post-stroke recovery by using backward walking through parallel bars (Yang, Yen, Wang, Yen, & Lieu, 2005). Also there is evidence of the positive effect of translational backward walking on balance in children (Hao & Chen, 2011). In sum: Backward walking procedures may help to increase the quality of life of specific groups of patients.

A secondary aim of this study is to check if there are differences between kinematic properties of original backward walking compared to reverse forward walking: Previous studies have found kinematic differences between forward and backward walking. For instance, translational forward and backward walking in 11 healthy subjects differed in head and trunk stabilization and speed as they were measured with an image processor of recorded video footage: In general, angular dispersion of spine segments (rotational movement of the trunk) and walking speed were lower during backward walking in comparison with forward walking (Nadeau, Amblard, Mesure, & Bourbonnais, 2003). More recently, a kinematic and kinetic analysis of 3D motion capture during forward and backward walking in 31 healthy subjects found decreased walking speed and cadence in backward walking compared with forward walking (Lee, Kin, Son, & Kim, 2013).

In sum, we expect to have a way to explore sensitivity and bias correspondent to original forward and backward walker conditions and their reversed displays including the analysis of these effects by body parts.

EXPERIMENT

METHOD

Participants. 14 students of psychology at the KU Leuven (13 women, 1 man, M_{age} = 18.95 years, SD_{age} = 0.46 years), participated in this experiment. The study was approved by the Ethical Committee of the Faculty of Psychology and Educational Sciences of the University of Leuven and in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki. Participants provided written informed consent (following the consent procedure approved by the Ethical Committee). One participant was under 18 (age 17.96). For this participant we did not obtain consent from their parents or legal guardians, because the Ethical Committee of our faculty urges this only for participants under the age of 16.

Stimulus. The basic signal stimulus consisted of a full point-light human walker in profile orientation going either backwards or forwards. The point-light walker was designed: 1) Using motion translational data from a young adult and healthy male walker going either forwards or backwards during capture routines performed at a laboratory room adapted as a studio of the Biomotion Lab at the KU Leuven and a modification of a 3D animation technique previously developed at the same lab (Dekeyser et al., 2002; Vanrie & Verfaillie, 2004), and 2) Making the two actions loopable to avoid abrupt changes of the position of point-lights during the animation: To achieve this, we applied the procedure described in Appendix C. The full forward walker animation was created with MATLAB for Windows XP to play 68 still images (for one step cycle, consisting of two steps) with a frame refreshing rate of 60 Hz on the screen of a Dell monitor. Each image in the full body version consisted of 13 white dots positioned on the major joints of the walker (the head, two shoulders, two elbows, two wrists, two hips, two knees, and two ankles; radius = 3 pixels) on a gray background. The walker subtended 4 cm at a viewing distance of 45 cm. The reversed forward walker animation was generated by playing back the forward walker animation. The backward walker animation and its correspondent reversed animation were created applying the same procedures but using 91 still images. Upper body and lower body forward/backward

walkers were generated drawing only the dots corresponding to the upper and lower joints of the full body, respectively.

Procedure and design. The experiment was run in a dimly lit and sound-attenuated lab room. The participants were instructed first and practiced to press the ’f ‘ on the keyboard when they perceived a figure as walking forward and the button ‘b’ when they perceived a figure as walking backward. After this practice, forward and backward stimuli were displayed in two separate blocks of trials. The original forward walker and its reversed display were presented for about 3.4 sec and the original backward walker and its reversed display were presented for about 4.6 sec. These durations corresponded to three gait cycles: The gait cycle lasted about 1.33 sec for the original forward walker and about 1.52 sec for the original backward walker. Just before the beginning of each block, the set of all correspondent stimuli to a block of forward or backward stimuli was shown in an ordered sequence: six conditions (two types of motion x three body parts). The two types of motion were original and reversed and the three body parts were upper, lower, and full. Each block contained 120 trials. On each trial, participants were presented with a figure facing to the left and appearing at random positions within the central display area of the monitor on a trial-by-trial basis

A particular figure was randomly chosen without repetition from the six available conditions: In this way at the end of the block, 20 trials in each of the six conditions were presented. After each stimulus was presented, a response screen appeared asking whether the figure was moving forward or backward. The participant had to press the ‘f’ or ‘b’ button before automated feedback was provided (by indicating if the response was right or wrong) and after each block of trials (by giving the percentage of correct responses in the block).

RESULTS

As we have mentioned before, we used a paradigm in which participants had to identify the direction of articulated motion of signals (original forward or backward walkers) or noise (reversed forward or backward walkers). A signal detection analysis was performed (classifying original motion as the “signal” and reversed motion as the “noise”)

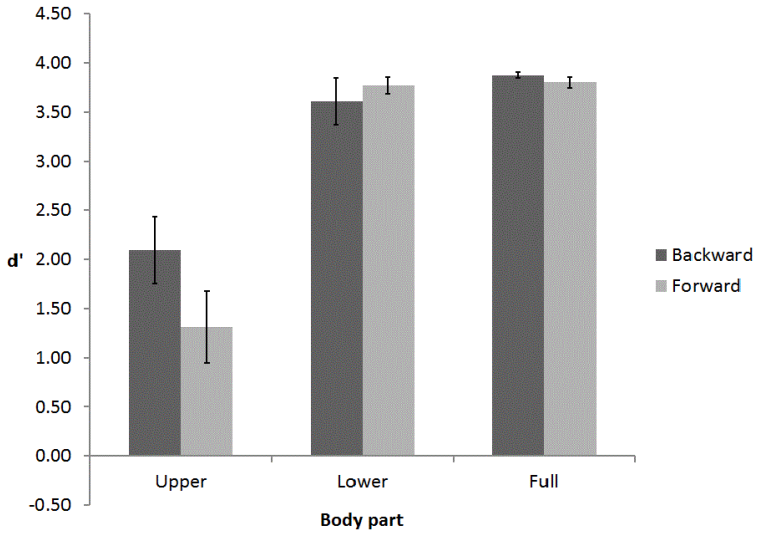

Figure 26. **d' (including standard error bars) as a function of direction of articulation and noise level.**

Values of d' (Figure 26) were analyzed using a repeated measures two-way analysis of variance (ANOVA) having as within-subjects factors the direction of original articulation (going either forwards or backwards) and body part (upper, lower, and full). The ANOVA yielded no significant main effect of the direction of original articulation, $F(1, 13) = 1.979$, $p = .183$. Mauchly's test indicated that the assumption of sphericity for body part had been violated ($\chi^2(2) = 11.485$, $p < .05$). Therefore degrees of freedom for this factor were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = .619$). There was a significant main effect of body part, $F(1.24, 16.09) = 47.74$, $p < .001$. Post-hoc comparisons showed d' for upper conditions ($M = 1.70$, $SD = 1.02$) < d' for lower conditions ($M = 3.691$, $SD = .46$), $p < .001$ and full body conditions ($M = 3.839$, $SD = .11$), $p < .001$. d' for lower conditions ($M = 3.691$, $SD = .46$) did not differ from d' for full body conditions ($M = 3.839$, $SD = .11$), $p = .674$. Mauchly's test indicated that the assumption of sphericity for the interaction between the direction of articulation and body part had been violated ($\chi2(2) = 10.962$, $p < .05$). Therefore degrees of freedom for this factor were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = .625$). The interaction between the direction of real articulation and body part was not significant, $F(1.25, 16.26) = .250$, $p = .128$. Actually there was a ceiling effect for the lower and full body figures.

Values of c (Figure 27) were analyzed in a similar way. The ANOVA yielded a significant main effect of the direction of original articulation, $F(1, 13) = 11.943$, $p = .004$. Post hoc comparisons showed c for original forward conditions ($M = .05$, $SD = 0.12$) > c for original backward conditions ($M = -.108$, $SD = .09$), $p = .002$. There was also a significant main effect of body part, $F(2, 26) = 8.046$, $p = .002$. Post hoc comparisons showed c for upper conditions ($M = -.112$, $SD = .15$) < c for lower conditions ($M = .042$, $SD = .09$), $p < .001$. Mauchly's test indicated that the assumption of sphericity for the interaction between the direction of articulation and body part had been violated ($\chi^2(2) = 15.432$, $p < .001$). Therefore degrees of freedom for this factor were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = .580$). The interaction between the direction of original articulation and body part was significant, $F(1.16, 15.08) = 17.363$, $p = .002$.

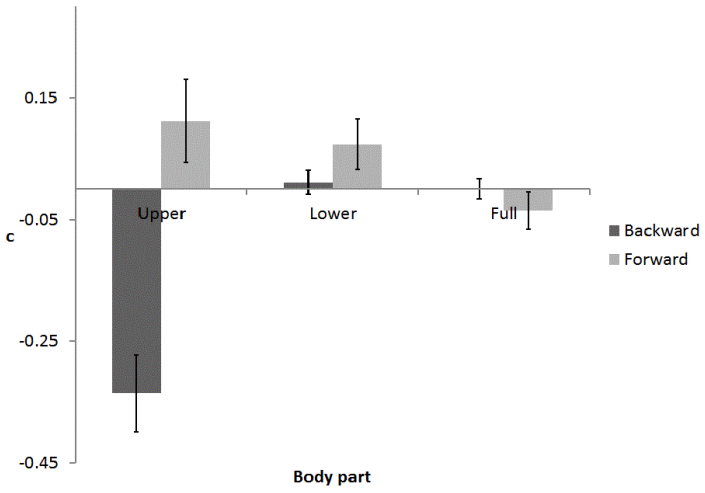

Figure 27. **c (including standard error bars) as a function of direction of articulation and noise level.**

DISCUSSION

These results suggest that participants performed alike when they had to detect original backward conditions and their reversed displays or when they had to detect original forward conditions and their reversed displays. These results also suggest that participants performed worse for the upper body conditions in comparison with the lower and full body conditions when they had to detect original forward or backward motion and their

correspondent reversed displays. Moreover, inspection of upper walker sensitivity values in Figure 26 may suggest that participants performed better to detect the original backward condition and its reversed display in comparison with the detection of the original forward condition and its reversed display. We did not test this hypothesis but it would be suggestive for future research to test it.

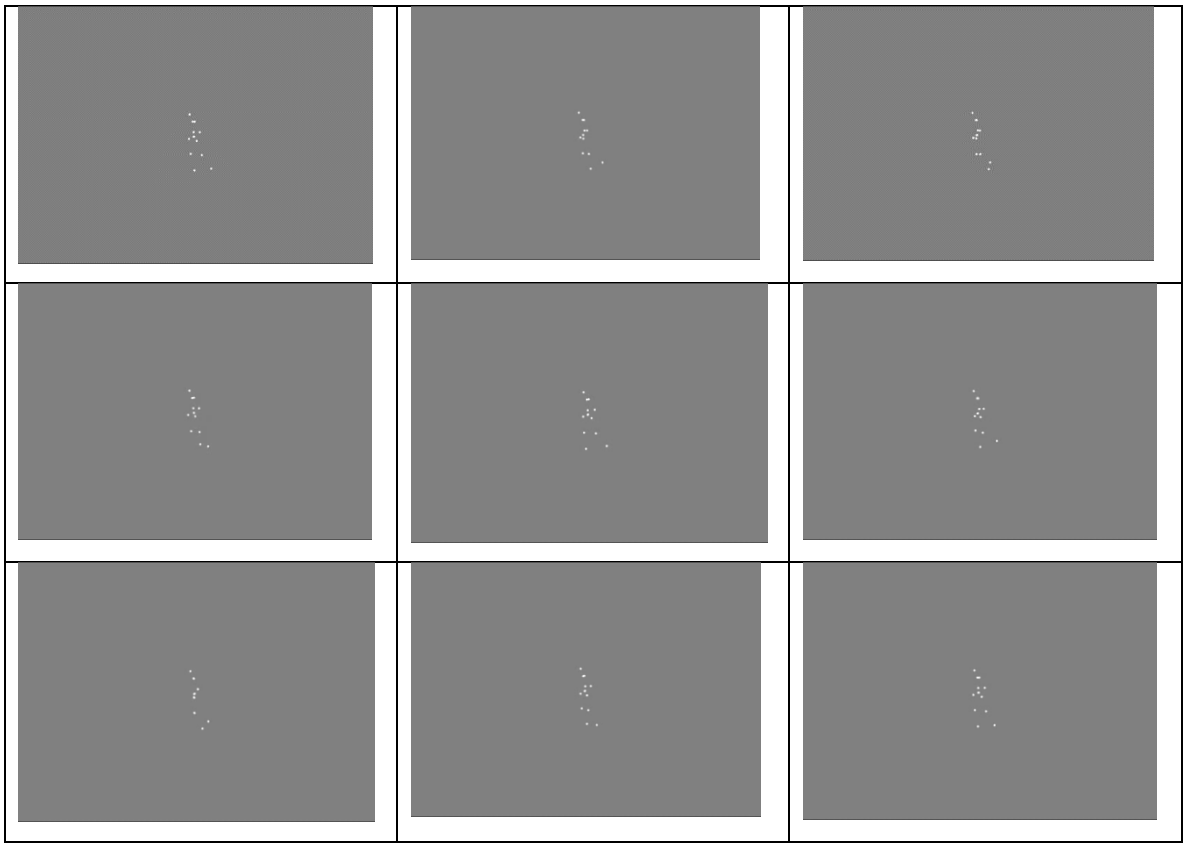

Figure 28. **Excerpt of the original forward stimulus. Each frame is spaced in time by 50 msec.**

Inspection of upper walker bias values in Figure 27 also suggests that participants had a greater bias when they responded to original backward motion and its reversed display than when they responded to original forward motion and its reversed display. As this bias had a negative value, we may conjecture that they perceived the arms of the upper body figure originally moving backwards and its reversed moving forwards as "legs", giving rise to a negative bias to perceive the original upper figure as going "forwards" and its reversed display as going "backwards".

In Figures 28 and 29 we depict excerpts of the original forward and backward stimuli: We mentioned in the Method section that the gait cycle of the original forward walker lasted about 1.33 sec and that of the original backward walker lasted about 1.52 seconds: The speed of original backward motion was lower than the speed of original forward motion. This kinematics coincides with previous findings on translational backward motion mentioned in the Introduction section (Nadeau, Amblard, Mesure, & Bourbonnais, 2003, Lee, Kim, Son, & Kim, 2013).

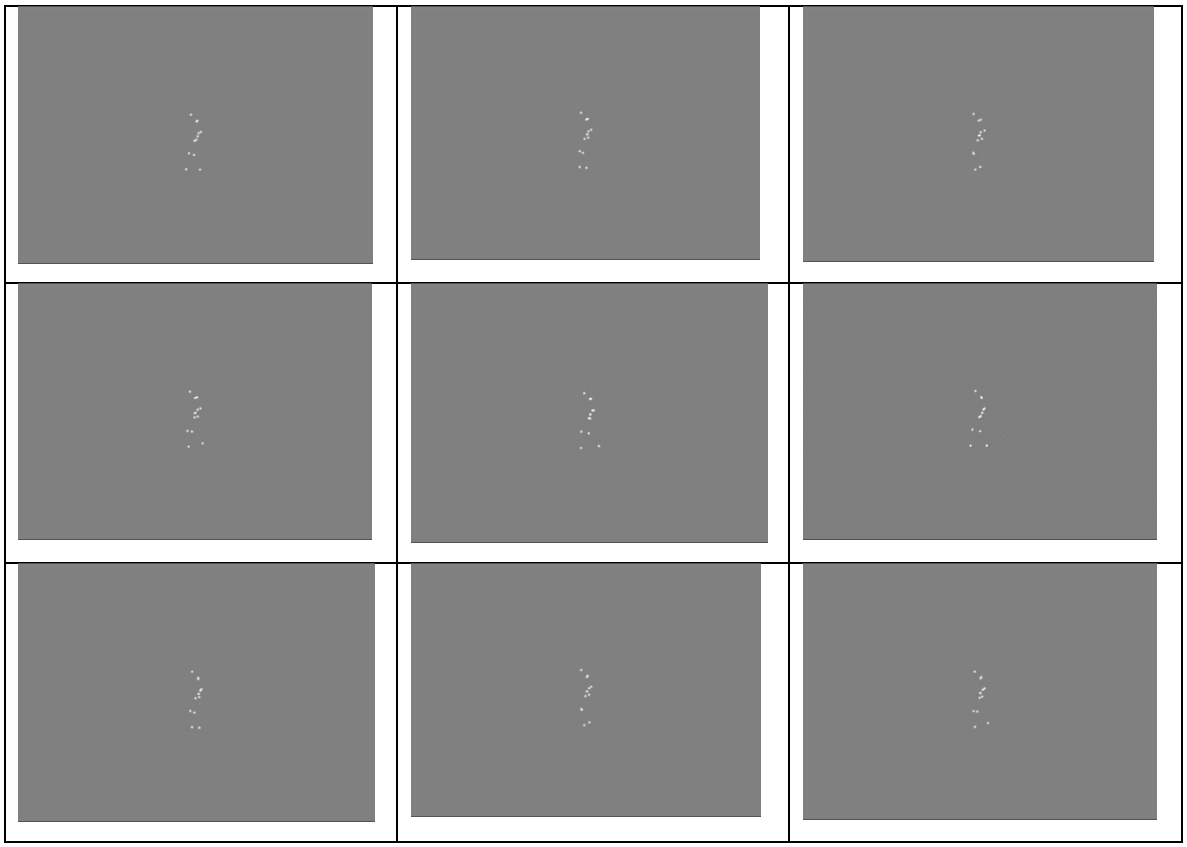

Figure 29. **Excerpt of the original backward stimulus. Each frame is spaced in time by 50 msec.**

Our findings reported in this chapter suggest that original translational backward motion is an action of its own and the using of the correspondent animation action as if on the treadmill may help to link conclusions of studies in biological motion perception using point-light displays to two domains of knowledge: 1) Neuropsychological rehabilitation. Future specific clinical protocols for rehabilitation of patients with motoric impairment or

disability associated to neurological conditions, might be understood in terms of the interlacing between perception and action of backward gait. We informed in the Introduction section the existence of clinical studies already using translational backward gait tasks with Parkinson's disease and post-stroke patients and healthy children to improve balance. More recently, translational backward gait tasks have been applied in studies with patients suffering of dementia (Johansson, Lundin-Olsson, Littbrand, Gustafson, Rosendahl, & Toots, 2017) and cerebral palsy (Abdel-Aziem & El-Basatiny, 2017). Dobkin (2006, p. 41) indicates in a textbook on neural repair and rehabilitation that retraining gait in patients "start with interventions to control of the head and trunk when necessary". Precisely, the kinematics of head and trunk distinguishes translational forward from translational backward gait and this kinematics might be associated to sensory feedback needs of a patient when is moving backwards and also to her/his perceptual capacities to distinguish between forward and backward motion of her/his own upper body part or of others, and 2) The current neurophysiological understanding points to the existence of common neural control structures involved in forward and backward gait as Hoogkamer, Meyns, and Duysens,(2014) argue. However, the supporting evidence referred by these authors corresponds to the specific analysis of translational motion of the lower limb already reviewed in the Introduction section of this chapter (Viviani et al., 2011): A future understanding of backward gait as a global action that involves perception and action of the body and its parts might contribute offering novel insights for future basic and applied experimentation.

Chapter 6

General conclusions

ABSTRACT

The purpose of the present chapter is to summarize our results. We recapitulate our empirical findings and methodological novelties, make our concluding remarks with a description of implications of our findings, propose open questions and offer a brief prospective for possible future research.

EMPIRICAL FINDINGS

PERCEPTION OF THE DIRECTION OF ARTICULATION OF WALKING: THE SIMULTANEOUS MASKING-PARADIGM

In Chapter 2 we investigated perception of articulatory motion in point-light figures using the simultaneous-masking paradigm. The task consisted of detecting the signal (a forward or backward normal walker) and the noise (a scrambled walker) within clouds of moving noise dots for simultaneous masking (30, 20, or 10 noise dots). We did not find any effect on sensitivity or bias of direction of motion and found a significant main effect of amount of noise.

PERCEPTION OF THE DIRECTION OF ARTICULATORY MOTION OF POINT-LIGHT FIGURES INVOLVED IN DIFFERENT ACTIONS

In Chapter 3 we investigated perception of motion direction on the basis of the articulatory relative motion of the limbs for four actions: walking, crawling, hand walking, and rowing varying: 1) the visible body part (upper, lower, vs. full body) and 2) the viewpoint (0° or sagittal, 30°, 60° and 90° or frontal view). Each action had specific body parts eliciting higher sensitivity to discriminate between forward and backward motion: For walking the lower part was most informative, for crawling both upper and lower body parts, and for hand walking and rowing, the lower part. In addition, sensitivity was worst for the frontal view of any of these four actions. We did not find any consistent effect on biases.

PHASE PORTRAIT ANALYSIS OF ACTIONS

In Chapter 4 we analyzed the association of kinematic indexes of asymmetry of speed, acceleration or their combination (phase portrait index) with performance for each of the four experiments reported in Chapter 3. We did these analyses for each action through Pearson correlations between sensitivity and each index: VIA that measures asymmetry of direction of speed, AIA that measures asymmetry of direction of acceleration and PPIA that measures their combination as a phase portrait. Kinematic indexes developed in Chapter 4 and sensitivity data of experiments reported in Chapter 3, were also used to estimate the amount of explained variance of indexes for dots or dots grouped by body parts or viewpoint. Kinematic indexes were explanatory of performance.

PERCEPTION OF REAL FORWARD AND BACKWARD MOTION IN POINT-LIGHT WALKERS

In Chapter 5 we compared perception of forward and backward point-light walkers versus their reversed displays. The task consisted of detecting the direction of original articulated motion (forward or backward normal walking) and the noise (their reversed versions) varying the visible body part (upper, lower, vs. full body). We did not find any effect on sensitivity of the direction of original articulation and found an effect of body parts. We did find an effect of direction, body parts and their interaction on bias.

METHODOLOGICAL NOVELTIES

KINEMATIC INDEXES AND PHASE PORTRAIT

In Chapter 4 we have applied the phase portrait graphical representation and introduced a new technique to estimate information on asymmetry of the direction of articulated motion in horizontal velocities and accelerations of point-light dots: kinematic indexes (VIA, AIA, $\widetilde{PPIA}$ and PPIA). They provide information on the size of asymmetries in either velocity, or acceleration or both of dots or groups of dots.

CONCLUDING REMARKS

In the Experiment reported in Chapter 2 we did not find any effect on sensitivity or bias of direction of motion and found a significant main effect of amount of noise using a simultaneous-masking paradigm to compare normal and scrambled full walkers going either forwards or backwards. These results may be linked to the results of Experiment 1 reported in Chapter 3 for the walking action in which there were effects of body part on sensitivity to distinguish between a forward and a backward walker. Specifically these effects were caused by sensitivity differences for direction of articulation between the upper body and the lower body or between the upper body and the full body and not between the lower and full bodies. We may conclude after these considerations that: 1) Detection (the forward/backward stimuli were presented in different blocks and in each block, the normal/scrambled stimuli were presented in different trials) of a forward normal and a forward scrambled full walker does not differ from the detection of a backward normal and a backward scrambled full walker, and 2) Detection of a forward normal and a backward normal full walker does not differ from the detection of a forward normal and backward normal lower walker (forward/backward stimuli were presented in different trials depicting the full, upper or lower body). However, this detection was more efficient in Experiment 1 of Chapter 3, probably because the stimuli in this experiment were unmasked and the detection task was for walkers with opposite direction of articulation while in the Experiment of Chapter 2, the stimuli were masked and the detection was for normal and scrambled walkers going either forward or backward in each block.

Findings in Chapter 3 (Davila, Schouten, & Verfaillie, 2014) suggest that each action had specific body parts eliciting higher sensitivity to distinguish between forward and backward motion as it has been described lines above. Similarly to the fact that information on direction of articulated motion is carried by the motion of the ankle in the case of walking (Saunders et al., 2010), we may conclude that information is carried by all limbs in the case of crawling and upper limbs in the case of hand walking and rowing.

In Chapter 4 we correlated kinematic indexes (VIA, AIA, $\widetilde{PPIA}$ and PPIA) of the amount of asymmetry between forward and backward motion and sensitivity data from Chapter 3. We found that these indexes were explanatory of sensitivity or equivalently,

differences in detection of forward and backward point-light animations of actions performed with lower body (walking and crawling) and upper body (crawling, hand walking and rowing).

Putting together commented results of Chapter 3 and 4, we may assert that we have found a way to understand psychophysically, how kinematic properties of body parts are associated with detection of the direction of articulated motion in point-light animations. Additionally, we have developed a new set of procedures to quantify the asymmetry between opposite directions of articulated motion and use it to make predictions. Our findings of Chapter 3 and our predictions of Chapter 4 were also consistent with the well-known fact of the poor informative value of the frontal point of view on determination of the direction of articulated motion (Kuhlmann et al., 2009).

In Experiment 2 of Chapter 3 we found higher biases when the upper part of a walker was shown irrespective of the viewpoint that varied from 0° (sagittal) to 30°, 60° and 90° (frontal). In this case when the upper body was shown the subject had to decide on the direction of an ambiguous stimulus and because of this uncertainty, we think that it was likely to get biased responses based on several factors such as previous similar perceptual or motoric experience or even a hardwired based tendency to perceive articulated direction of motion as going forwards. However, we found similar and lower biases when the upper, lower or full part of a walker was shown in sagittal view in Experiment 1 of Chapter 3. Probably, the walker point-light animation is not suitable to produce consistent biases across subjects.

In Experiments 3 and 4 of Chapter 3, we found low and similar biases irrespective of the body part or orientation shown. Kinematic analysis in Chapter 4 for crawling (action displayed in Experiment 3 of Chapter 3) suggests that information on the direction of articulated motion is carried both by the upper and lower parts of the body. As both parts are informative, maybe low and similar biases in responses to their displays are associated to the unambiguous kinematic characteristics of the action. Kinematic analysis in Chapter 4 for hand walking (action displayed in Experiment 4 of Chapter 3) suggests that information on the direction of articulated motion is carried by the upper part of the body. In this case, we found low biases in responses to the display of the upper part that was informative but also in responses to the display of the lower part that was not informative.

In Experiment 5 of Chapter 3 we found a significant effect of orientation on biases. Rowing (action displayed in the experiment) diverges from the previous discussed actions as it has been described before in that chapter. Kinematic analysis of the action in Chapter 4 suggests that information on direction of articulated motion is carried by the upper limbs, specifically by wrists and elbows in profile, 30° and 60° viewpoints. In frontal view, kinematic information on direction of articulated motion is clustered (values of kinematic indexes correspondent to all joints are closer than in other viewpoints) and additionally, magnitudes of indexes are smaller than those of non-frontal viewpoints. We found complex patterns in biases (see Figure 10 in Chapter 3) that may be attributed to the complexity of the action. We also found a complex pattern in biases for hand walking (see Figure 10 in Chapter 3) but in this case differences among viewpoint conditions were not significant.

In the Experiment of Chapter 5, there were effects of body parts on sensitivity: differences between distinguishing a forward from a reversed forward walker or between a backward from a reversed backward walker. Specifically these effects may be attributed to sensitivity differences to detect direction of articulation between the upper body and the lower body and between the upper body and the full body and not between the lower and full bodies. An inspection of Figure 26 in Chapter 5, may indicate that sensitivity differences were higher for the detection of the backward and the reversed backward upper walkers than for the detection of forward and the reversed forward upper walkers. We did not test this hypothesis but it would be suggestive for future research to test it.

In the Experiment of Chapter 5 we found effects of direction of original articulation and body parts on bias. An inspection of Figure 27 in Chapter 5, suggests that bias differences were higher for the detection of the backward and the reversed backward upper walkers than for the detection of the forward and the reversed forward upper walkers. We did not test this hypothesis but for future research, we may focus our analysis on upper walkers and check if direction of articulation causes differences in biases.

Finally, results of Chapter 3 and Chapter 5 suggest two main consistent conclusions for walking displayed in profile view: 1) Detecting direction of articulated motion depends on the direction of motion of the lower part of the body, specifically ankle kinematics may contribute to make informative lower body dynamics as it has been suggested before

(Saunders et al., 2010), and 2) Performance to detect direction of articulated motion decays when only the upper part of the body is displayed.

OPEN QUESTIONS

A central issue in our research has been to apply kinematic tools for the analysis and post-hoc prediction of performance in detection of articulated motion: We varied actions and displays of body parts and viewpoints. The task of detecting direction of articulated motion in point-light displays may depend on available unambiguous kinematic information in animations, previous perceptual and/or motoric experience, or even the way we interpret the animated stimulus. Considering our results from Chapters 3 and 4, we may assert that in the case of sensitivity, available kinematic information seems to be explanatory of performance to distinguish between different directions of articulated motion.

Here an issue of potential interest for future research is to find empirically and precisely how detection of direction of articulation is produced: For instance, psychophysical operations may take place at the level of sensorial processing using kinematic information in a straightforward way. But higher cognition processes including retrieval from long-term memory, attentional strategies, or interpretation of the motion may also take place. A way to disentangle these diversity of factors would be surveying participants before and after experiments to get information on their relevant previous perceptual/motoric experience and their understanding of depicted actions in experiments and include these data as covariates in the analysis of experimental results. Other possibility would be motoric training to perform unfamiliar actions and posterior comparison of detection of direction of articulated motion between trained participants and untrained counterparts or even comparison of performance of the same subjects exposed to trained and untrained conditions.

As we have mentioned before, we failed to find biases effects or consistent biases effects with the exception of orientation in the case of rowing in Experiment 4 of Chapter 3 and direction of original articulation and body parts in the Experiment of Chapter 5. Further empirical exploration is needed to identify critical dimensions to elicit perceptual ambiguity and/or its measurement as it has been done before, for instance, for facing bias effects (Schouten et al., 2011; Schouten, Davila, & Verfaillie, 2013).

Another issues of interest is familiarity with actions, in the case of a familiar action such as walking, efficiency to distinguish natural forward from natural backward articulated motion may be attributed not only to kinematic cues but also to previous motoric and perceptual experience. However, in the case of crawling (Experiment 3 of Chapter 3), performances in detecting direction of motion were very similar to performances for walking (Experiment 2 of Chapter 3), despite being an action that we may consider less familiar unless we assume crawling perception as hardwired in the human brain.

POSSIBLE FUTURE RESEARCH

Perception of direction of articulated motion in biological motion is a proper research topic to disentangle bottom-up and top-down driven processes. As we mentioned in Chapter 1, there is an ongoing debate on the causality direction of processes that drive perception of biological motion (Thornton, 2013) and mixed evidence favoring either bottom-up or top-down explanations. A way to shed light on these issues for the specific topic of direction of articulation, might be kinematic analyses of actions as we did in this dissertation and its use to predict performance. An accurate description of the kinematics of single and grouped dots correspondent to diverse actions and features such body parts and orientations, may help to build quantitative explanatory rules of performance in detection of direction of articulation tasks. This approach would fall within the "detection and direction" line already discussed in Chapter 1 and, more specifically, would be closely related to the search of psychophysical laws of biological motion perception. As the kinematic indexes we created were an attempt to measure asymmetry of direction of motion and found them useful to predict performance, we may link our evidence on asymmetry of speed and acceleration of moving figures going forwards or backwards to theoretical discussions of symmetry and asymmetry perception and the identification of psychophysical laws. Van der Helm (2010), for instance, argues that detectability of symmetry in the presence of noise follows a psychophysical law that deviates from the Weber-Fechner law. In our research reported and analyzed in Chapters 3 and 4, lack of asymmetry as it is measured and portrayed by kinematic indexes and phase portrait figures, may be studied systematically to examine if variations of this asymmetry for body parts or points of view, follow psychophysical laws.

It became evident in our research that kinematic analysis is useful to compare features such as body parts or viewpoints and distinguish among informative and non-informative features. When the kinematic information is expressed like asymmetries in speed and accelerations of dots or groups of dots moving forward or backward, higher asymmetry values were associated with more informative parts or viewpoints and lower asymmetry values with less informative parts. These findings suggest that at least, in perception of articulated motion, the kinematic properties of the moving figures are explanatory when there are asymmetries between opposing directions of articulated motion for specific features.

The phase portrait representations and the kinematic indexes we have developed to measure asymmetry for the case of the direction of articulated motion could be applied to the analysis of a diversity of point-light stimuli used in biological motion perception studies: For instance, coherent vs. incoherent walkers or upright vs. inverted walkers, or even limited-lifetime and scrambled walkers. Specifically, the technique could be useful to characterize in terms of kinematic properties the symmetry or asymmetry of velocity and acceleration correspondent to specific body parts and viewpoints of these kind of stimuli. As an example, we may consider a limited-lifetime figure: How its phase portrait would look like? How its kinematic indexes would be? Would this information be of some value to explore the richness of this figure as a psychophysical stimulus?

As we did in Chapter 4, it would be possible to relate the kinematic indexes we have to performance and, going further, also to bias: It would be of interest to find ways to disentangle different contributions to bias by the using of the kinematic indexes. If, for example, bias when perceiving a particular point-light figure were correlated to VIA or AIA of the lower part but not to VIA or AIA of the upper part of that figure, then we would have a way to disentangle physical and non-physical factors producing bias.

In a similar way as we did for Chapter 4, the analysis of body parts and viewpoints using the new technique could be stretched and include a diversity of point-light actions. These considerations might be of potential interest for a diversity of disciplines that are related with perception and action of the body and probably fields such as movement sciences and applied disciplines such as kinesiology may find useful the analysis of symmetry of actions in several practical domains: physical rehabilitation, exercise, physical activity, sports, among others. For instance, suppose we capture the action of walking of two elders

who are learning to walk "again" after two severe cerebrovascular accidents, we could use phase portrait representations to appreciate the progress of these patients walking forward or backward on the treadmill, through parallel bars or in an open field. Another field that could be receptive to the adoption of phase portrait descriptions is clinical neurology. Specifically in the sub-domain of movement disorders the application of phase portrait representations and kinematic indexes may help to describe objectively the kinematics of clinical signs such a tremor or a ballistic movement.

When we started this research, we expected to find differences in detection of forward and backward walking based on the possible existence of motoric influences of biological motion perception (Casile & Giese, 2006, Calvo-Merino et al., 2006). As we failed to find these differences in Chapters 2, 3, and 5 when using full body depictions, we may assert that detection of direction of articulated motion of walking would not depend on potential motoric influences because these motoric influences would have become noticeable making detection of forward walking more effective than detection of backward walking in our experiments. Even, with findings reported in Chapter 5, we discarded possible effects due to the use of reversed displays of forward walking in Chapters 2 and 3. Probably, it is the case for an impoverished stimulus as a point-light display but might not be the case when more information is available as may occur if stick figures or more enriched stimuli are used.

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Appendices

APPENDIX A

VIEWING POINT-LIGHT ANIMATIONS FROM DIFFERENT VIEWPOINT ANGLES

Vanrie (2005, p. 43) asserts: "We would like to contribute to the diversity of stimuli in the domain of action perception by presenting a set of moving stimuli involving human actions under point-light conditions as seen from different viewpoints". Vanrie indicates that the Leuven Action Database contains for each individual action, 3-D coordinates files that correspond to five different viewing angles: two lateral (90°), two 45°, and a frontal (0°) view. These files were generated by offline processing using 3D Studio.

In Chapter 3 we described the stimuli we used for Experiments 2, 3, 4, and 5 which consisted respectively of point-light animations of walking, crawling, hand walking, and rowing actions depicted in four viewpoints or orientations: profile (0°), 30°, 60°, and frontal (90°). It is important to stress that Vanrie's lateral orientation corresponds to our frontal orientation and Vanrie's frontal orientation corresponds to our profile orientation.

In our research, to generate different viewpoints for each experiment, we used 3-D coordinates correspondent to three of our four actions from the Leuven Action Database (walking, crawling, and rowing) and one (hand walking) to a source from Red Eye Studio (2002) as it has been detailed in Chapter 3. In all cases, these 3-D coordinates were positions for the profile orientation. As in our experiments we had the purpose to depict an action from trial to trial from a different viewpoint, we generated the 30°, 60°, and frontal 3-D coordinates by the following transformation correspondent to a counter clockwise rotation on the plane XY about the Z axis:

$$\begin{bmatrix} \boldsymbol{x\ rotated} \\ \boldsymbol{y\ rotated} \\ \boldsymbol{z\ rotated} \end{bmatrix} = \begin{bmatrix} \boldsymbol{cos(angle)} & \boldsymbol{-sin(angle)} & \mathbf{0} \\ \boldsymbol{sin(angle)} & \boldsymbol{cos(angle)} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{1} \end{bmatrix} \begin{bmatrix} \boldsymbol{x\ in\ profile\ view} \\ \boldsymbol{y\ in\ profile\ view} \\ \boldsymbol{z\ in\ profile\ view} \end{bmatrix}$$

APPENDIX B

MATLAB CODE TO GENERATE POINT-LIGHT ANIMATIONS FROM DIFFERENT VIEWPOINT ANGLES

```
clear all
close all
wd=cd;
load 'action_0.txt'
angle = input('Please write down an angle value between 0 and 360 and press ENTER\n','s');
angle = str2num(angle)
rot_matrix_1=[1 0 0; 0 cosd(angle) -sind(angle); 0 sind(angle) cosd(angle)];
rot_matrix_2=[cosd(angle) 0 sind(angle); 0 1 0; -sind(angle) 0 cosd(angle)];
rot_matrix_3=[cosd(angle) -sind(angle) 0; sind(angle) cosd(angle) 0; 0 0 1];
a= rot_matrix_1*action_0';
b= rot_matrix_2*action_0';
c= rot_matrix_3*action_0';
filename1_angle=c'
save action_angle.txt action_angle /ascii
```

APPENDIX C

LOOPABILITY OF ACTIONS

Vanrie (cf. supra) asserts when referring to actions available at the Leuven Database of Point-Light Actions: "…, all actions except one can be looped, in the sense that there are no abrupt changes in the location of the dots in the transition from the final frame of the action back to the first one. For most actions this also follows the natural flow of the movement (e.g. cycling, walking, or rowing), for a few others this repetition might be less natural (drinking, shooting, playing pool)".

In Chapter 3 we reported that a point-light human hand walker was created using Autodesk 3ds Max 2012 (2011) and a .csm file produced by Red Eye Studio (2002). As the csm source contained coordinates that corresponded to hand walking with translation, we needed to smooth the transition from the final frame to the first one of this action.

To achieve this purpose, we developed a procedure to smooth transitions by cancelling abrupt changes through the animation sequence: First, we built three Cartesian graphs for each dot (39 graphs = 3 graphs/dot times 13 dots) with the number of frames as the variable at the horizontal axis and the position of the dot at the x-, y-, or z- dimension at the vertical axis. Second, we detected abrupt changes in any of these dimensions by visual inspection and comparison of the values correspondent to the first and the last frame. Third, we healed these abrupt changes by using equivalent smoothed data to replace no smoothed data: for instance, position data of the right shoulder to heal abruptness of motion of the left shoulder. To achieve this purpose we took advantage of symmetrical properties of the coordinated motion of limbs and used convenient mathematical transformations (rotations about the horizontal axis and translations through the vertical axis) to calculate new positions and use them to replace the original positions causing abrupt changes. Alternatively, when equivalent data from the contralateral joint was also not smooth, we healed abrupt changes of a joint of interest by iterative linear interpolation of its positions through frames: for instance, interpolation between the last and the first frames.

APPENDIX D

MOTION CAPTURE AND 3D ANIMATION TECHNIQUE ADAPTATION

In Chapter 5, we informed that the point-light walker was designed using motion capture data from a walker going either forwards or backwards and a modification of a 3D animation technique (Dekeyser et al., 2002; Vanrie & Verfaillie, 2004). In Table 16 that follows, we summarize and compared what Vanrie (2005) did and what we have done: First, we used a more modern software version for motion capture, tracking, and offline analysis of data. Second, we used a more modern version for 3D computer animation and extraction of coordinates.

Table 16

Summary of motion capture and animation techniques reported by Vanrie (2005) and those used in the current project.

Dissertation	Vanrie (2005)	Davila (2017)
Motion capture software	Qualysis MacReflex	Qualysis 2.0.379
Number of markers used for acquisition	30	30
Position of markers used for acquisition	Based on Vicon's Body Builder 3.5 Manual	Based on Vicon's Body Builder 3.5 Manual
Motion capture output format	CME	TSV
3D computer animation software	Character Studio and 3D Studio Max	3ds Max
3D computer animation input format	CSM	CSM

Alex Ernesto Dávila Dávila

Perception of the direction of articulatory motion of point-light figures